इंटरनेट मानक

## Disclosure to Promote the Right To Information

Whereas the Parliament of India has set out to provide a practical regime of right to information for citizens to secure access to information under the control of public authorities, in order to promote transparency and accountability in the working of every public authority, and whereas the attached publication of the Bureau of Indian Standards is of particular interest to the public, particularly disadvantaged communities and those engaged in the pursuit of education and knowledge, the attached public safety standard is made available to promote the timely dissemination of this information in an accurate manner to the public.

"जानने का अधिकार, जीने का अधिकार"
Mazdoor Kisan Shakti Sangathan
"The Right to Information, The Right to Live"

"पुराने को छोड नये के तरफ"
Jawaharlal Nehru
"Step Out From the Old to the New"

IS 14902-2 (2001): Performance of High-Voltage d.c. (HVDC) Systems, Part 2: Faults and Switching [ETD 40: HVDC Power Systems]

"ज्ञान से एक नये भारत का निर्माण"
Satyanarayan Gangaram Pitroda
"Invent a New India Using Knowledge"

Act Number 22 of 2005
The Indian Parliament
RIGHT TO INFORMATION

Made Available By
Public.Resource.Org

"ज्ञान एक ऐसा खजाना है जो कभी चुराया नहीं जा सकता है"
Bhartṛhari—Nītiśatakam
"Knowledge is such a treasure which cannot be stolen"

BLANK PAGE

BRUTUM FULMEN

IGNORANTIA JURIS NON EXCUSAT

PROTECTED BY COPYRIGHT

**IS 14902 (Part 2) : 2001**
**IEC 60919-2 (1991)**

*भारतीय मानक*

# उच्च-वोल्टता डी.सी. (एच वी डी सी) प्रणाली की कार्यकारिता

## भाग 2 दोष एवं स्विचिंग

*Indian Standard*

# PERFORMANCE OF HIGH-VOLTAGE d.c. (HVDC) SYSTEMS

## PART 2 FAULTS AND SWITCHING

ICS 29.200; 29.240.99

© BIS 2001

**BUREAU OF INDIAN STANDARDS**
MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG
NEW DELHI 110002

*January* 2001

**Price Rs 450.00**

High Voltage Direct Current Power Systems Sectional Committee, ET 40

## NATIONAL FOREWORD

This Indian Standard (Part 2) which is identical with IEC 60919-2 (1991) 'Performance of high-voltage d.c. (HVDC) systems — Part 2 : Faults and switching' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the High Voltage Direct Current Power Systems Sectional Committee (ET 40) and approval of the Electrotechnical Division Council.

This International Standard is one of the series, which deals with performance of HVDC systems. The Number of this IEC Publication [which was earlier IEC 919-2 (1991)] stands redesignated by IEC as mentioned above.

The series comprises the following IEC standards:

| *Publication No.* | *Title* |
|---|---|
| IEC 60919-1 (1988) | Performance of HVDC systems — Part 1 : Steady-state conditions |
| IEC 60919-2 (1991) | Performance of HVDC systems — Part 2 : Faults and switching |
| IEC 60919-3 (1999) | Performance of HVDC systems — Part 3 : Dynamic conditions |

This standard (Part 2) being identical with IEC 60919-2 is to be read with IS 14902 (Part 1) : 2000. Part 3 of this standard aligning with IEC 60919-3 will be taken up in due course.

Certain conventions are, however, not identical to those used in Indian Standards. Attention is drawn particularly to the following:

a) Wherever the words 'International Standard' appear referring to this standard, they should be read as 'Indian Standard'; and

b) Comma (,) has been used as a decimal marker while in Indian Standards, the current practice is to use a point (.) as the decimal marker.

Only the English text of the IEC Publication has been retained while adopting it in this Indian Standard, and as such the page numbers given here are not the same as in IEC Publication.

## CROSS REFERENCES

In this adopted Standard, reference appears to certain International Standards for which Indian Standards also exist [(*see also* (Part 1) of this standard)]. The corresponding Indian Standards which are to be substituted in their respective places are listed below along with the latest IEC Publications, besides giving the degree of equivalence:

| *IEC Pub No. with Year Referred to* | *Latest IEC Pub No. with Year* | *Title of the Latest IEC Publication* | *Corresponding Indian Standard* | *Title of Indian Standard* | *Degree of Equivalence* |
|---|---|---|---|---|---|
| 71-1:1976 | 60071-1 (1993) | Insulation co-ordination — Part 1 : Definitions, principles and rules | 2165 (Part 1): 1977 | Insulation co-ordination : Part 1 Phase to earth insulation co-ordination, principles and rules | Not equivalent |

(*Continued on third cover*)

# CONTENTS

Page

Clause

1 General ............ 5

1.1 Scope ............ 5
1.2 Normative references ............ 5

2 Outline of HVDC transient performance specifications ............ 6

2.1 Transient performance specifications ............ 6
2.2 General comment ............ 7

3 Switching transients without faults ............ 7

3.1 General ............ 7
3.2 Energization and de–energization of a.c. side equipment ............ 7
3.3 Load rejection ............ 10
3.4 Start–up and shut–down of convertor units ............ 11
3.5 Operation of d.c. breakers and d.c. switches ............ 11

4 A.C. system faults ............ 15

4.1 General ............ 15
4.2 Fault categories ............ 15
4.3 Specification matters affecting transient performance ............ 15
4.4 Specification impact on control strategy ............ 21

5 A.C. filters, reactive power equipment and a.c. bus faults ............ 22

5.1 General ............ 22
5.2 Transient overvoltages in filter banks ............ 22
5.3 Transient overcurrents in filter and capacitor banks ............ 23
5.4 Capacitor unbalance protection ............ 24
5.5 Examples of protection of filters and capacitor banks ............ 24
5.6 Shunt reactor protection ............ 26
5.7 A.C. bus protection ............ 26

6 Convertor unit faults ............ 31

6.1 General ............ 31
6.2 Types of convertor unit faults ............ 31
6.3 Short circuits ............ 31
6.4 Failure of convertor unit to perform its intended function ............ 32

Clause Page

6.5 Convertor unit protection ........ 33
6.6 Additional protection aspects of series connected convertor units ........ 35
6.7 Additional protection aspects of parallel connected convertor units ........ 36

7 D.C. reactor, d.c. filter and other d.c. equipment faults ........ 39

7.1 General ........ 39
7.2 Fault types ........ 39
7.3 Protection zones ........ 39
7.4 Neutral protection ........ 39
7.5 D.C. reactor protection ........ 41
7.6 D.C. harmonic filter protection ........ 41
7.7 D.C. harmonic protection ........ 42
7.8 D.C. overvoltage protection ........ 42
7.9 D.C. side switching protection ........ 43

8 D.C. line faults ........ 46

8.1 Overhead line faults ........ 46
8.2 Cable faults ........ 47
8.3 D.C. fault characteristics ........ 47
8.4 Functional d.c. fault detection requirements ........ 47
8.5 Protective sequence ........ 47
8.6 Fault protection schemes ........ 49
8.7 Open circuit on the d.c. side ........ 50
8.8 Power line cross protection ........ 50

9 Earth electrode line faults ........ 50

9.1 General ........ 50
9.2 Specific requirements – Earth electrode line ........ 51
9.3 Electrode line supervision ........ 51

10 Metallic return conductor faults ........ 52

10.1 Conductor for the return circuit ........ 52
10.2 Metallic return faults ........ 52
10.3 Fault detection – Metallic return ........ 53
10.4 Metallic return fault protection systems ........ 53

11 Insulation co–ordination - HVDC systems ........ 59

11.1 General ........ 59
11.2 Protection schemes using surge arresters ........ 59
11.3 Switching overvoltages and temporary overvoltages on the a.c. side ........ 59

Clause Page

11.4 Switching overvoltages and temporary overvoltages on the d.c. side .................... 60
11.5 Lightning and steep fronted surges .................... 60
11.6 Protective margins .................... 61
11.7 Arrester duties .................... 62
11.8 Prevention of protective relay action due to arrester currents .................... 65

11.9 Insulation clearances .................... 65
11.10 Creepage distances for the insulation .................... 65

12 Telecommunication requirements .................... 71

12.1 General .................... 71
12.2 Specific requirements - Telecommunication systems .................... 71
12.3 Consequence of telecommunication system outages .................... 72
12.4 Special considerations for power line carrier (PCL) systems .................... 72

13 Auxiliary systems .................... 73

13.1 General .................... 73
13.2 Electrical auxiliary systems .................... 73
13.3 Mechanical auxiliary systems .................... 75

ANNEX A (informative) - Bibliography .................... 78

As in the Original Standard, this Page is Intentionally Left Blank

# *Indian Standard*

# PERFORMANCE OF HIGH-VOLTAGE d.c. (HVDC) SYSTEMS

## PART 2 FAULTS AND SWITCHING

## 1 General

### 1.1 *Scope*

This report provides guidance on the transient performance and fault protection requirements of high voltage direct current (HVDC) systems. It concerns the transient performance related to faults and switching for two-terminal HVDC systems utilizing 12-pulse convertor units comprised of three-phase bridge (double way) connections. Excluded are multi-terminal HVDC transmission systems. However, certain aspects of parallel convertors and parallel lines, if part of a two-terminal system, are discussed. The convertors are assumed to use thyristor valves as the bridge arms, with gapless metal oxide arresters for insulation co-ordination and to have power flow capability in both directions. No consideration is given herein to diode valves.

The report is comprised of three parts. Part 2 of this report is accompanied by companion documents, Part 1 for steady-state and Part 3 for dynamic performance. An effort has been made to avoid duplication in the three parts. Consequently users of this Report are urged to consider all three parts when preparing a specification for purchase of a two-terminal HVDC system.

Readers are cautioned to be aware of the difference between system performance specifications and equipment design specifications for individual components of a system. While equipment specifications and testing requirements are not defined herein, attention is drawn to those which could affect performance specifications for a system. Note that detailed seismic performance requirements are excluded from this document. In addition, because of the many possible variations between different HVDC systems, these are not considered in detail. Consequently this report should not be used directly as a specification for a specific project, but rather to provide the basis for an appropriate specification tailored to fit actual system requirements for a particular electric power transmission scheme. This report does not intend to discriminate the responsibility of users and manufacturers for the work specified.

### 1.2 *Normative references* *

The following standards contain provisions which, through reference in this text, constitute provisions of this report. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this report are encouraged to investigate the possibility of applying the most recent editions of the standards listed below. Members of IEC and ISO maintain registers of currently valid International Standards.

---

* A non-exhaustive bibliography of IEC publications for information purposes is given in Annex A.

### 1.2.1 *IEC Standards*

71-1: 1976, *Insulation co-ordination. Part 1: Terms, definitions, principles and rules.*

146: 1973, *Semiconductor convertors.*

633: 1978, *Terminology for high-voltage direct current transmission.*

700: 1981, *Testing of semiconductor valves for high-voltage d.c. power transmission.*

### 1.2.2 *IEC Reports*

919-1: 1988, *Performance of high-voltage d.c. (HVDC) systems. Part 1: Steady-state conditions.*

919-3: xxxx, *Performance of high-voltage d.c. (HVDC) systems. Part 3: Dynamic conditions.* (Under consideration.)

## 2 Outline of HVDC transient performance specifications

### 2.1 *Transient performance specifications*

A complete performance specification related to transient performance of an HVDC system during faults and switching should also include fault protection requirements.

These concepts are introduced at the appropriate locations in the following transient performance and related clauses:

Clause 3 - Switching transients without faults.

Clause 4 - A.C. system faults.

Clause 5 - A.C. filter, reactive power equipment and a.c. bus faults.

Clause 6 - Convertor unit faults.

Clause 7 - D.C. reactor, d.c. filter and other d.c. equipment faults.

Clause 8 - D.C. line faults.

Clause 9 - Earth electrode line faults.

Clause 10 - Metallic return conductor faults.

Clause 11 - Insulation co-ordination - HVDC systems.

Clause 12 - Telecommunication requirements.

Clause 13 - Auxiliary systems.

Discussion in the following clauses on the d.c. line, earth electrode line and earth electrode is limited to the relationships between these and either the transient performance or protection of HVDC convertor stations.

### 2.2 *General comment*

In general, control strategies can be used to minimize the effect of disturbances, but when the safety of equipment depends on their correct performance, this should be identified.

## 3 Switching transients without faults

### 3.1 *General*

This clause deals with the transient behaviour of the HVDC system during and after switching operations both on the a.c. and the d.c. sides of convertor substations, and is not related to equipment or line faults which are treated in the following clauses of this report (Part 2).

Switching operations without faults can be classified as follows:

1) energization and de-energization of a.c. side equipment such as convertor transformers, a.c. filters, shunt reactors, capacitor banks, a.c. lines, static var compensators (SVC), and synchronous compensators;

2) load rejection;

3) starting and removal from service of convertor units;

4) operation of d.c. breakers and d.c. switches for paralleling of poles and lines; connection or disconnection of d.c. lines (poles), earth electrode lines, metallic return paths, d.c. filters, etc.

### 3.2 *Energization and de-energization of a.c. side equipment*

During the operating life of an HVDC transmission system, energization and de-energization of convertor transformers, a.c. filters, shunt reactors, capacitor banks, SVCs, and other equipment may occur many times. Depending on the characteristics of the a.c. system and the equipment being switched, resulting current and voltage stresses will be imposed on equipment being switched and generally impinge as well on part of the overall a.c. system.

The overvoltages and overcurrents which are critical for plant design are usually due to faults (Clauses 4 to 8), and not to normal switching operations. Nevertheless, they are discussed here for completeness. They are relevant in consideration of disturbances to a.c. system voltages.

Filter switching will also result in transient distortion of the bus voltage. This could disturb the commutation process and in a weak system could lead to commutation failure.

Thus equipment switching should be investigated to:

- determine critical a.c. network and equipment conditions which may contribute to such abnormal stresses and actions which may be taken to mitigate them;
- design the equipment;
- verify arrester duties.

Transients occur routinely when filters and capacitor banks are switched as necessary to control harmonic interference and steady-state terminal voltages.

Because of the frequency of occurrence of switching overvoltages it is generally desirable that the overvoltage protective devices do not absorb appreciable energy during such operations. For example the amplitudes of overvoltages arising from routine switching operations can be minimized by the use of suitable resistors incorporated in the circuit-breakers associated with filters and capacitor banks or by synchronizing the closing of the circuit-breakers. This can also reduce the possibility of inverter commutation failures. The HVDC control system can also be used effectively to damp certain overvoltages.

Restrike-free switching devices should be used for capacitor switching to avoid onerous overvoltages from restriking which otherwise could occur when disconnecting filters or capacitor banks.

Transformer energization inrush currents can cause an undesirable interaction in the a.c. and d.c. systems. They can last several seconds with initial peaks of at least three to four times the transformer rated current. Oscillatory modes can be excited and lightly damped temporary overvoltages can appear if the transformer is working in its magnetic saturation region. Another result is the injection into the network of low order harmonic currents of high magnitude. These often produce voltage distortion to which the inverter could be sensitive, leading to possible commutation failures.

To reduce inrush currents, typical control measures include circuit-breaker pre-insertion resistors, synchronization of breaker poles, or setting of the transformer on-load tap changers at their highest tap positions. However it should also be noted that saturation of already energized convertor transformers can arise from energization of another transformer in the convertor station or from switching of an SVC.

Also the application of low order harmonic filters can be helpful in reducing the problems with inrush currents. The effectiveness of such measures depends largely on the system and pertinent equipment characteristics. In addition the response of the a.c. system can be sensitive to the number of convertor transformers already energized, especially if they are not yet loaded as for series connections of multiple convertor units.

The energization of capacitor and filter banks produces oscillations between these elements and the rest of the network. Again, depending on the size of the banks and the network characteristics, switching overvoltages can appear along with overcurrents in the already energized a.c. system components.

Attention should be paid to the possibility of damage to the capacitors during re-energization of capacitors because of trapped charges in the capacitors from a preceding opening operation. Measures may be necessary for discharging them before reclosing if their internal discharge resistors are not sufficiently effective within the desired switching time. Alternatively, a longer switching time may be necessary.

Energization of filters excites the frequencies to which they, in combination with the a.c. network, are tuned. Also switching out of filter and capacitor banks can cause the a.c. system voltage to oscillate.

SVCs can be provided to stabilize the voltage and control temporary overvoltages. Energization of SVCs should be such as to produce a light or even no transient in the system voltage. Most of them have an active control which can be used to accomplish this objective.

Connection or disconnection of shunt reactors and capacitors produces change in a.c. voltage. Size and operation of this equipment should be specified so as to limit switching-caused voltage changes to acceptable levels.

Energization and de-energization of a.c. transmission lines connected to HVDC sub-stations generate voltage transients as well, which should be taken into account. These operations change the a.c. harmonic impedances which also influence the transient harmonic effects.

Synchronous compensators can produce voltage transients when started and operated as induction motors, drawing reactive power and reducing the system voltage. This aspect of their performance should be carefully examined.

A table of acceptable levels of temporary or transient overvoltages and overcurrents during switching operations of the various system components or preferably a diagram of the expected transient overvoltage and overcurrent levels versus time should be developed for the specifications.

Related to the foregoing, information about the electrical characteristics of the a.c. system and its future development as complete as possible should also be supplied in the specifications. Relevant operating criteria along with existing and expected a.c. overvoltage levels should also be shown.

The desired performance of the HVDC substations under the transient conditions described in the foregoing subclauses should be stated for both switching in and out of the various components.

Overvoltage performance for the HVDC link should be co-ordinated with the actual performance characteristics of the existing a.c. network with which it is to be integrated.

### 3.3 *Load rejection*

Sudden reductions of transmitted power over the HVDC link without occurrence of faults could take place:

- due to unintentional tripping of the a.c. circuit-breakers at either terminal;
- due to blocking and bypass of convertor units as a consequence of control system action;
- due to loss of generation and for a multitude of other possible causes.

Voltage levels on the a.c. system would rise primarily because of the consequent excess of reactive power compensation at the HVDC substation. Resonant conditions can be reached due to saturation of the power transformers and resonances between transformers, filters and the a.c. network. These overvoltage effects can be accentuated by frequency deviations in the a.c. system.

Special care shall be taken for the case that the inverter becomes isolated from the a.c. system with only the filters and shunt capacitor banks connected to it. For this contingency the inverter shall be blocked and bypassed to prevent overvoltage-caused damage to the filter components or the a.c. side arresters or the valve arresters. Opening of the remote end circuit-breakers, for a system with a single or only a few lines connecting the inverter to the a.c. system shall be taken into account in the design of the protective scheme.

Load rejection transients following system faults are discussed in 4.3.5.

Acceptable load rejection-caused overvoltages, in terms of amplitudes and durations should be specified particularly if the resulting stresses are expected to be greater than those discussed in 3.2.

Suitable operating strategies to return to normal operating conditions should be developed. Among the procedures for achieving this are controlling the convertor units still in service to regulate the system voltage or switching in reactors or by removal of capacitor or filter banks. If capacitor or filter banks are to be switched under overvoltage conditions this shall be taken into account when fixing the associated circuit-breaker ratings and capabilities. In cases when an existing circuit-breaker of inadequate capacity could be called on to perform this duty, its operation should be inhibited and other means used to reduce overvoltages.

When convertors are to be used for voltage control, consideration should be given to the design and manufacture of the valves for operation at large delay angles.

The extent to which convertor measures can be used for reducing a.c. system overvoltage will depend on the requirements for continuity of supplied power to satisfy the a.c. system dynamic performance.

Other means, such as switched capacitors or reactors, synchronous compensators, SVCs, special metal oxide (MO) temporary overvoltage absorbers (TOV), etc. may need to be used to limit overvoltages to acceptable levels and to achieve the desired convertor performance.

As in most system design decisions, economics will play a major role. However, trade-offs may be necessary between cost and system performance.

### 3.4 *Start-up and shut-down of convertor units*

Normal operator-initiated start-up and shut-down procedures for an HVDC pole should be established.

Start-up and shut-down of series-connected convertor units is performed by the control system sometimes in conjunction with the operation of switching devices in parallel with the convertor units. For this purpose normally an automatic sequence is followed in which a valve bypass path within the bridge is activated before the opening or closing of the bypass switch.

For this procedure any special requirements or constraints such as the maximum allowable a.c. bus voltage variation, special interlock requirements or maximum variation in transmitted power, etc., should be specified.

Whether the system is to be operated with a smaller number of convertors than in the ultimate configuration, particularly during the development stages of the project, should be noted.

### 3.5 *Operation of d.c. breakers and d.c. switches*

Switching devices have been used on the d.c. side of HVDC transmission systems for several functions as follows:

- by-pass and disconnect convertor units;
- connect or disconnect the substation pole to the earth electrode line in bipolar links;
- connect poles or bipoles in parallel, including polarity reversal;
- switch the neutral bus-bar;
- connect or disconnect the d.c. line;
- connect or disconnect d.c. filters;
- connect d.c. filters in parallel during monopolar operation.

They can be classified with respect to various aspects. Figure 1, page 14, gives an example of switching device arrangements on the d.c. side of a convertor substation with the following meanings:

- current commutating switches (S);
- disconnectors (D);
- earthing switches (E).

Distinctions should be made between:

- devices which are used for opening at zero current, even though they may have limited making and breaking capability;
- devices which are able to transfer the current from one current path to a parallel one; such devices shall have an adequate energy absorption capability for the expected current interruption during the transfer;
- and d.c. breakers which are able to interrupt any d.c. current within their ratings and withstand the following recovery voltage.

In the future d.c. breakers may be used in order to allow an unrestricted paralleling or de-paralleling of substation or d.c. line poles. A special application of the d.c. breaker is the metallic return transfer breaker (MRTB).

Zero current operated switches and d.c. circuit-breakers with a current interrupting capability not exceeding the load current shall be co-ordinated with the control system actions under both fault conditions and during operating sequences. For example, substation or line pole paralleling and de-paralleling operations require the opening and closing of various switches.

These operations initiate a wide variety of voltage and current transients and such functions are performed during established operating sequences as determined by the d.c. controls.

Thus, the transients depend on the control system, on the switch operating times and the a.c. and d.c. system electrical characteristics.

For a two-terminal system where reliability requirements are stringent, the use of d.c. circuit-breakers offers the possibility of enhancing transmission reliability and availability by the use of transmission lines in parallel and sectionalized along their routes. This would permit isolation of one of the parallel lines or line sections either in the case of a permanent fault or for operating needs without even a momentary shut-down of the d.c. transmission.

Thus maximum transmission capability within the thermal limits of the remaining healthy circuit could be maintained. Of course, selective protections as in the case of parallel a.c. lines would need to be used.

The operating characteristics including speed requirements should be determined and specified for all switches and circuit-breakers required for the contemplated HVDC transmission.

When specifying d.c. switching devices, the following duties shall be defined:

- the function within the HVDC substation;
- modes of operation;
- operation time requirements;
- continuous current;
- current on opening;
- current on closing;
- voltage on opening;
- voltage across open contacts;
- voltage to earth in the closed and in the open position.

In the event of a low impedance fault to earth on the d.c. side of one pole, at least one neutral switch should be able to transfer the current injected into the earth from the operating pole.

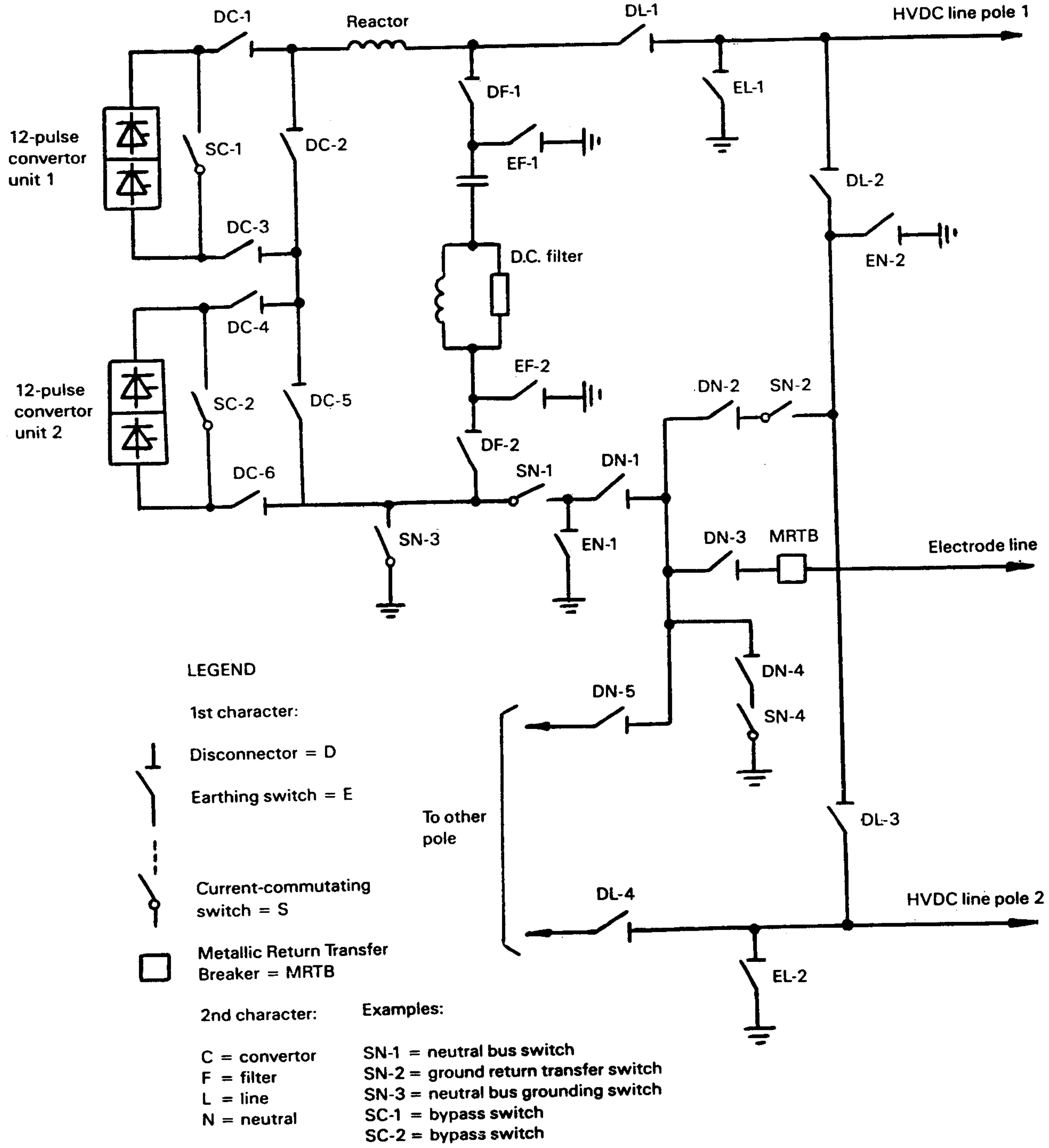


Figure 1 – D.C.-side switches for an HVDC substation with series-connected convertor unit

## 4 A.C. system faults

### 4.1 *General*

Transient performance of an HVDC system during a.c. system faults and during the recovery period immediately following fault clearing are important considerations in the specification and design of such a system. Recovery performance as influenced by implementation of specific control strategies will directly affect the ratings of the HVDC equipments, the connected a.c. substation facilities and the connected a.c. network response.

### 4.2 *Fault categories*

The following a.c. faults should be considered when preparing an HVDC system specification:

- sending end (rectifier) and receiving end (inverter) faults for each power flow direction;
- three-phase, three phase-to-earth, phase-to-phase, two phase-to-earth and single phase-to-earth faults at the HVDC substations; of these, analysis of d.c. system performance during three-phase and single phase-to-earth faults should be sufficient for most planning purposes;
- a.c. faults remote from the HVDC substations; reclosing practices should be considered;
- various faults as above in a.c. or d.c. lines in cases where there is a parallel a.c. line closely coupled to the d.c. line. The extreme case of this type is a flashover from an a.c. to a d.c. conductor where a.c. and d.c. lines cross.

### 4.3 *Specification matters affecting transient performance*

HVDC specifications concerning transient performance during and after a.c. system faults should consider all affected areas of the d.c. and a.c. system operation and equipment ratings. To achieve an optimum balance between total system costs and performance, trade-offs should be considered in the HVDC specifications.

Characteristics that influence transient performance during and after a.c. system faults are discussed in the following paragraphs.

#### 4.3.1 *Effective a.c. system impedance*

In its simplest form effective a.c. system impedance is usually expressed as the Short-Circuit-Ratio (SCR), that is, the ratio of the a.c. system short-circuit MVA to convertor d.c. power (MW) rating.

However, SCR is more precisely expressed as a.c. system admittance on a base of rated d.c. power and a.c. voltage. This is defined at system frequency and should include an angle. For many studies the total admittance seen by the convertor is relevant, including that of filters and other reactive power elements connected to the HVDC substation a.c. bus; this is known as Effective Short-Circuit Ratio (ESCR). Most significant are the impedances at the low-order harmonic frequencies.

SCR as defined here differs from the ratio RSC defined in IEC Publication 146-1-1 where the base is the rated MVA of the convertor.

Transient fault performance factors affected by the SCR are:

1) power transfer during faults to maintain stable operation without commutation failures;
2) recovery time, especially for inverter end faults;
3) control of post-fault recovery voltages within acceptable limits;
4) possible low frequency resonance conditions, i.e., < 5th harmonic;
5) temporary overvoltages.

All of these factors become more pronounced with increases in the a.c. system impedance and phase angle.

### 4.3.2 *Power transfer during faults*

The HVDC system may be sensitive to relatively remote a.c. system faults where a.c. voltage changes at the HVDC a.c. buses are not large. Voltage depression and distortion associated with a.c. faults affect the delay angles of the convertors and cause a reduction in the transmitted d.c. power. For remote three-phase faults the power loss is essentially proportional to the a.c. voltage drop, down to a level of d.c. voltage where some form of voltage dependent control possibly needs to be imposed, as discussed in the following paragraphs. A further power reduction can take place as a result of a control mode shift as described in 4.3.8.

Voltage dependent control provides a means to modify the current limits or orders of the convertors at each terminal in a co-ordinated manner without loss of current margin. The d.c. voltage at each end represents a common signal to both the rectifier and inverter terminals for co-ordination without the necessity for other communications. There are a variety of such controls; an example characteristic is shown in figure 2, page 21.

In case the convertors are used for reactive control, the input voltage for the voltage dependent control should be the a.c. bus voltage.

System studies should be made to determine optimum settings for d.c. or a.c voltage thresholds, current limits, and time constants or ramp rates, if any, for each system.

For a.c. single phase-to-earth faults to or near the rectifier terminal, the reduction in power transfer for modern convertors is also approximately proportional to the average a.c. voltage drop, since delay angle unbalance can be readily incorporated to compensate for large a.c. voltage dissymmetries.

On the other hand, for most inverter control strategies using equidistant firing schemes, the earliest firing time which is set to minimize commutation failures, fixes the firing time for all valves. This control action in conjunction with voltage dependent control normally results in minimum power transfer during a.c. single-phase inverter end faults. Strategies that transfer to individual-phase control operation during inverter end a.c. line-to-earth faults offer one means for increasing the power transfer from the aforementioned minimum without experiencing an excessive number of commutation failures.

Power transfers achievable under a.c. fault conditions depend largely on the characteristics of the HVDC system under consideration and therefore can best be determined by digital and/or simulator studies.

### 4.3.3 *Recovery following fault clearing*

The recovery time can be defined as that time required after the fault clearing for the HVDC system to recover to a specified level of the prefault power, typically to 90 %, with the overshoot and settling time being specified.

HVDC system recovery times can be fast, e.g. 50-100 ms, with modern control systems for all non-permanent a.c. faults at the rectifier or inverter for low impedance a.c. systems. In practice however many HVDC systems being designed or installed are connected to high impedance a.c. systems at either HVDC substation. In such case, recovery times can be several times longer than for HVDC systems connected to low impedance a.c. systems. Long recovery times can also be expected for HVDC systems making use of long d.c. cables and very long d.c. overhead lines.

Recovery time settings shall take into consideration the a.c. system stability characteristics for both primary and possible backup fault clearing times.

However factors such as the necessity to minimize commutation failures or post fault recovery voltages often influence the actual recovery time implemented in a d.c. system control strategy.

Recovery can often be improved by maintaining, if possible, the d.c. current flowing even at a reduced magnitude by firing the valves during severe a.c. single-phase-to-earth and three-phase faults. Valve firing during the period of the fault or resumption of firing immediately upon fault clearing can also reduce the magnitude of recovery voltages and improve stability.

Specifications should indicate the expected duration of single-phase-to-earth and three-phase faults, including most likely backup clearing times, for which fast recovery capability of the HVDC system should be provided. This is important because some valves shall be designed with sufficient energy storage for the gating circuits to ride through expected fault periods.

### 4.3.4 *Reactive power consumption during fault and post-fault recovery periods*

Reactive power consumption of the HVDC substation during and after a.c. faults depends on its control strategy. Voltage dependent current limits with tailored characteristics are often utilized to modify the reactive power consumption as a function of voltage and to improve the inverter's ability to recover without commutation failures.

Strategies may be adopted for the remote unfaulted HVDC substation and where practical at the faulted substation to continue reactive power consumption or voltage support at a level to maintain a.c. bus voltages within prescribed limits.

During commutation failures, significant variations occur in reactive power flow. Persistent commutation failure in convertors followed by protective action result in reactive power flow being rejected into the a.c. system which can lead to substantial overvoltages on high impedance systems.

HVDC system studies are important to determine the required means to control voltages at the a.c. bus and to maintain commutation as well as stability of the interconnected a.c. networks.

### 4.3.5 *Load rejection due to a.c. faults*

Fault conditions which can result in convertor blocking, tripping of loads, failures to deblock upon clearing of three-phase faults and severe commutation failures, all result in forms of load rejection which can initiate large temporary overvoltages, ferroresonance, and a.c. system instabilities which can cause system collapse.

In addition on some a.c. systems careful attention shall be given to the possibility of large d.c. load rejections leading to self-excitation of generators or synchronous compensators at or electrically near the HVDC substation.

Load rejection overvoltages will have a direct impact on ratings of the HVDC equipment.

Studies should be carried out to assess:

- the extent to which existing equipment in the a.c. network can withstand these overvoltages and to design necessary corrective measures;
- design requirements for the HVDC substation equipment including any needed a.c. protection to satisfactorily withstand such load rejection overvoltages.

While not blocking, the convertor can be used to help limit overvoltages. However consideration shall be given to the possibility of convertor blocking during a.c. system faults with subsequent failures to recover. Such contingencies may indicate the need for other measures such as high speed switching devices for reactive power equipment, static var compensators (SVC), low order damped filters or protective energy dissipation devices to control load rejection overvoltages.

The specifications should state the acceptable overvoltage magnitudes and durations for the above contingencies.

### 4.3.6 *Switching of reactive power equipment*

Switching of reactive power equipment such as a.c. filters and shunt capacitor and shunt reactor banks is a common strategy at the a.c. terminals of HVDC substations for control of harmonic interference and steady-state terminal voltages, the latter as a function of a.c. system loading or of the primary a.c. system voltage.

When specifying the switching device to switch filters, shunt reactors or shunt capacitor banks, attention shall be given not only to the normal steady-state interrupting capability and speed, but also to the overvoltage requirements which may result from a.c. fault clearing and large load rejection.

Further complications may become apparent if an existing reactive power switching device is inadequate for safe interruption during temporary load rejection overvoltages, in which case provision shall be made for a backup breaker of adequate capacity to enable disconnection of excess reactive power sources.

Another consideration is that the use of switching devices can result in objectionably long restart times for the HVDC system if the switched reactive power equipment must be reinserted before the HVDC system may be loaded to prefault levels.

### 4.3.7 *Effects of harmonic voltages and current during faults*

Multiple cycle commutation failures or misfires occurring during an a.c. fault or the recovery period may cause currents and voltages at low-order non-characteristic harmonics and excite other frequencies, on the a.c. and d.c. sides. These may temporarily excite resonances in the a.c. or d.c. systems, but the resulting currents and voltages normally are not excessive, partly because of the damping provided by modern control systems. However, such effects should be studied to check the effect on, for example, filter transient ratings, and possible misperformance of a.c. system protective relays.

If the d.c. side is resonant at the fundamental frequency, saturation of the convertor transformers can occur. This would add to any second harmonic on the primary and cause possible system instability. Also an a.c. single-phase-to-earth fault near the rectifier terminal injects large second harmonic voltages on the d.c. side that will remain as long as firing continues. Because of these considerations it is advisable to study carefully the possibility of any resonance of the d.c. line to this harmonic.

Harmonics generated during faults should be taken into account in the design ratings for the a.c. filters and in determining the inverter's ability to commutate during fault recovery periods.

A further problem which should be carefully examined is possible misoperation of the a.c. protection due to low order harmonics during a.c. faults.

### 4.3.8 *Shift in control modes of operation*

Changes in operating modes, that is, to power or current control mode for example, may be necessary during a.c. fault conditions. Shifts from rectifier current control to inverter current control lead to a power reduction that require a current order adjustment to correct for the power loss. Also co-ordination of current margins with and without end-to-end communications and changes in reactive power demands with current margin correction should be investigated.

In some high impedance a.c. systems, unstable operations during fault-initiated transients can appear in the power control mode unless a switchover is made to current control, or the power control mode is made to assume constant current control mode characteristics.

### 4.3.9 *Power modulation on the HVDC system*

A.C. system transient stability and HVDC fault recovery performance sometimes can be improved by the use of power, direct current or direct voltage modulation. This option will be discussed in Part 3 of this report series.

### 4.3.10 *Emergency power reductions*

During fault conditions resulting in critical a.c. line outages, capability for emergency power reductions or even power reversals may be required as a contingency option to mitigate a.c. system instability. The specifications should consider the impact of such control actions on:

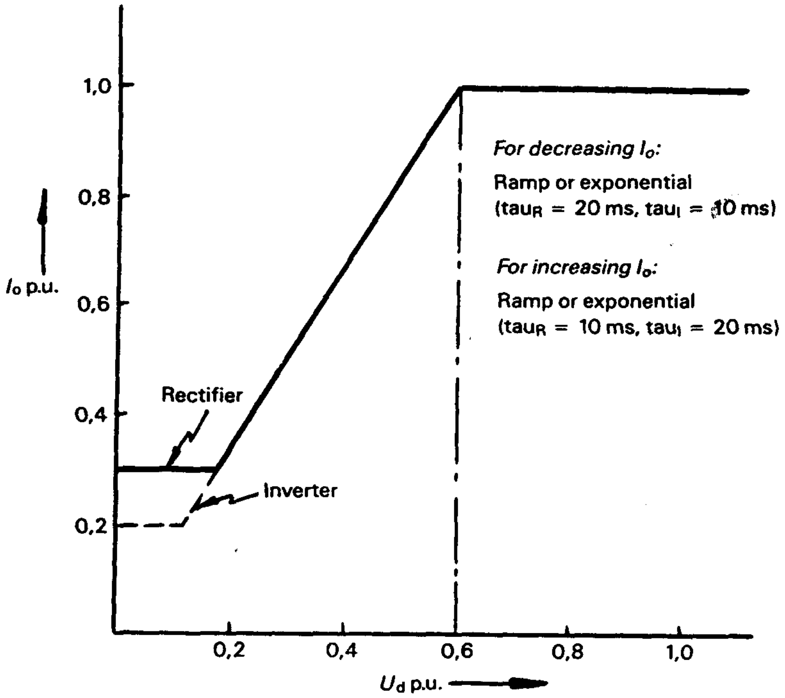
- possible overvoltages or destabilization of the a.c. system connected to the opposite end substation as a result of the partial load rejection;
- communications time requirements to co-ordinate the emergency reductions plus post-fault power increases and the impact of possible communications loss.

In some cases fault recovery from a.c. faults may permit operation of the d.c. system at a reduced power level until other restorative actions have been accomplished as determined by appropriate system studies.

### 4.4 *Specification impact on control strategy*

Because of the wide range of a.c. system conditions that shall be considered in determining optimum transient performance during a.c. faults and during the recovery period following fault clearing, no single control strategy will be appropriate for all cases. Each system shall be optimized around specified reference conditions as determined by digital computer and/or analog simulator studies for that particular system.

Performance specifications should permit d.c. control strategies which achieve an optimum compromise between maintaining power transfer and the prevention of commutation failures, instabilities or excessive recovery voltages, provided that the overall result is a satisfactory solution for the interconnected a.c. system.



NOTE - $U_d$ = d.c. voltage;

$I_o$ = current order;

tau$_R$ and tau$_I$ = rectifier and inverter time constants, respectively.

Figure 2 – Example of voltage dependent control characteristics

## 5 A.C. filters, reactive power equipment and a.c. bus faults

### 5.1 *General*

This clause discusses faults in a.c. harmonic filters, in reactive power equipment and faults on the a.c. busbar. Relatively high levels of harmonic currents which may appear in these items warrant a discussion of protection aspects. This is included. Specific fault protection aspects of SVCs are not covered in this document.

An example of the arrangement of a.c. filters and shunt capacitors for a bipolar HVDC scheme is shown in figure 3, page 27. The individual capacitor, reactor, and filter arms of the banks may be energized and de-energized by means of load disconnecting switches, but then earth faults within the bank shall be cleared by the bank circuit-breakers. An alternative arrangement, sometimes used is to connect the filter and the capacitor and reactor banks via tertiary windings on the convertor transformers.

The fundamental and harmonic frequency impedances of the filters and the reactive power banks have a major influence on the amplitude and waveshape of overvoltages occurring at the a.c. busbar. Therefore detailed representation of a.c. harmonic filters and reactive power banks is essential for studies of the busbar voltages during transient conditions.

### 5.2 *Transient overvoltages in filter banks*

During normal operating conditions most of the line-to-earth voltage will appear across the main capacitor of the filters, while the voltage across other filter elements is normally a small fraction of the line-to-earth voltage. However under transient conditions the prospective voltage across the filter reactors and resistors can be even higher than the normal line-to-earth voltage. Therefore surge arresters protection should be applied internally in the filters as discussed in clause 11.

In addition to the overvoltages occurring routinely as a consequence of normal switching (see clause 3), the filter components are likely to be subjected to lightning-caused overvoltages, switching surges and busbar or external close-in faults.

Since the filter capacitors exhibit low impedances to fast wavefronts such as from lightning discharges, the filter reactors and resistors will be almost directly exposed to any lightning overvoltages appearing on the a.c. busbar.

Switching surge overvoltages appearing on the a.c. busbars may be significantly magnified internally in the filters and the resulting component overvoltages may even exceed the a.c. busbar-to-earth voltage. Therefore the individual component overvoltages should be investigated during overvoltage studies. When the components are not directly protected by surge arresters, as is often the case for the main filter capacitors, they may need to be designed to withstand higher switching surge levels between their terminals than other directly protected equipment connected from the busbar-to-earth.

During unbalanced a.c. system faults, the convertors, if not blocked, will generate low order harmonics of substantial amplitude. If filters for low order harmonics are used, the filter surge arresters may be required to absorb considerable energy under these conditions. Another energy stress condition to consider particularly for filter reactor surge arresters of the second or third harmonic filters (when such filters are provided), is during energization of large transformers electrically close to the filter bus such as at recovery from a close a.c. fault.

Severe overvoltages with fast front times can occur across the resistors and reactors within the filters if a flashover from the a.c. busbar-to-earth should take place in the HVDC substation. The prospective voltage amplitudes across these filter elements will be equal to the pre-flashover voltages across the main filter capacitor and the surge arrester energy absorption requirement can be high.

## 5.3 *Transient overcurrents in filter and capacitor banks*

Under transient conditions peak currents in the filter components may be several times greater than the normal steady-state values.

In the event of a flashover from busbar-to-earth the capacitor banks will discharge energy into the fault. The current in this discharge will be limited by the stray inductance of the capacitor stack and its busbar connections and by the current limiting inductor if used. Similarly, where surge arresters are provided across reactors and resistors in a.c. harmonic filters, the capacitor discharge current can be high since it is only limited by the back e.m.f. of the protective device and by stray inductance.

Due consideration to these overcurrents should be given in the specifications of the components as well as of the protective circuits and the design of the earthing system. Thus capacitor fuses shall be capable of withstanding the discharge currents, and the operation of current transformers and protective relays should not be adversely affected nor should the protection be incorrectly triggered by transient currents which are within the capabilities of the filter components. These should be designed to withstand such discharges.

The analysis should consider the system configuration, including the filters and shunt capacitors, leading to the most critical stresses.

### 5.4 *Capacitor unbalance protection*

To achieve the desired harmonic performance and reactive power balance at all d.c. loadings the capacitor and filter banks are usually divided into a number of switchable arms. This means that the individual banks (arms) may be of relatively low Mvar rating, i.e., the number of parallel elements in the capacitor banks would be small.

During the operating life of a capacitor bank, capacitor elements can fail and be disconnected by fuse operation. When internal fuses are used, their operation disconnects the individual internal faulty element, while external fuse operation will disconnect the complete capacitor cell.

Capacitor banks are often designed to have built-in redundancy which means that a limited number of capacitor element failures and the accompanying fuse operations will not overstress the remaining healthy capacitors in the bank. However fuse operations should be detected so redundancy can be restored in the bank at an early convenient opportunity.

One method of such detection is use of current unbalance relay protection. For this scheme each capacitor phase is subdivided into two closely equivalent parallel groups of capacitors. Sensitive current unbalance relays responding to the difference in current in the branches are utilized to detect small changes resulting from capacitor element failure and subsequent fuse operation.

An alternative procedure uses voltage sensing devices which measure the voltage at tapping points in each phase of the capacitor bank to detect changes caused by failed capacitor elements and fuse operations. An overvoltage relay is used to monitor the phase or sum of the intermediate tapping voltages.

For some applications two levels of unbalance detection are used. The first gives an alarm and permits manual de-energization of the capacitor bank and replacement of failed capacitor units as necessary to restore redundancy. The second level gives an automatic trip signal to ensure that the safety of the remainder of the capacitor bank is not compromised as a consequence of the loss of a large number of capacitor units or elements. Unbalance protection schemes assume an extremely low probability of the same degree of capacitor element failure simultaneously in two branches of a filter capacitor bank.

### 5.5 *Examples of protection of filters and capacitor banks*

Examples of protection arrangements for filters and capacitor banks for an HVDC system are illustrated in figures 4, 5 and 6, pages 28 to 30. The choice is usually based on individual utility experience and practices.

If redundancy is sufficient to allow a pole to continue to operate even with one filter out of service, it may be desirable to protect the filter arms individually, so that the faulty filter can be disconnected rapidly with minimum loss of transmission capability.

If loss of a filter means that the pole cannot continue operation, it may then be considered economical to provide protection only for the overall bank or to include the filters in the busbar protection zone. As another alternative to individual filter protection, some operational restrictions such as reduction in transmitted power could be considered.

To ensure that the appropriate protection characteristics are applied, contingency operation requirements for partial loss of reactive power sources should be studied and specified.

The presence of an earth or phase-to-earth fault within a given protection zone can be detected by a conventional differential current protection system as shown in figure 4, page 28.

When filters are assigned their own individual protection zones, current transformers shall be provided in each phase on the a.c. busbar side and at the neutral side of the filter. When the filter bank is treated as a single protective zone, only one set of high voltage current transformers need be provided, situated in the a.c. busbar connections.

If tripping of the complete pole should be initiated when the filter bank is tripped, the filter bank could alternatively be incorporated in the overall pole differential protection scheme. However this will have the disadvantage of reduced automatic information for identification of the faulted bank.

Another zone protection scheme is the restricted earth fault protection shown in figure 5, page 29. This uses current transformers in each of the three high voltage phase conductors and in the neutral connections to detect an earth fault in the protected zone.

It should be noted that if the surge arresters inside the filter banks are connected directly to the substation earth mat, the arrester surge current may be registered by the protection system as an unbalance current. The resulting probability of undesirable relay operations can be minimized by proper co-ordination or by including the arresters in the protection zone.

The current in the filter and capacitor banks will depend not only on the amplitude and harmonic content of the a.c. busbar voltage, but on the integrity of the filter and bank components themselves. The differential current schemes described above may not be sufficiently sensitive to detect all internal breakdowns in the filters. Some of these incipient types of failures may need to develop sufficiently so that they can be detected and cleared.

Overcurrents which result from abnormal a.c. busbar voltages often can be tolerated for limited times without excessive penalties in terms of lost equipment life. However the equipment should be monitored so that mitigative steps may be taken before such overloads exceed the limits imposed by the known margins inherent in the equipment. For this, protection can be obtained by measuring the current in each phase and using overcurrent and overload relays. To ensure adequate protection against these problems in an a.c.

harmonic filter it is often necessary to provide current transformers for individual elements of the filter as shown in figure 6, page 30.

### 5.6 *Shunt reactor protection*

The protection arrangement for a shunt reactor applied at an HVDC substation for reactive power control is similar to that applied to a reactor or transformer as used in an a.c. transmission system.

### 5.7 *A.C. bus protection*

The convertor a.c. busbar is normally protected by a differential protection system. Since resonances can exist between the a.c. filters and the a.c. system a high content of harmonic currents may be present in the busbar currents during fault recovery periods. The busbar protection system then shall operate correctly in the presence of these harmonic currents.

Another aspect of this protection which should be examined is its performance during temporary overvoltage conditions. Under some conditions the peak voltages of one polarity may be substantially higher than the other. This can result in unidirectional surge arrester currents. It shall be ensured that the current transformers do not saturate under these conditions since misoperations of the protection can otherwise occur.

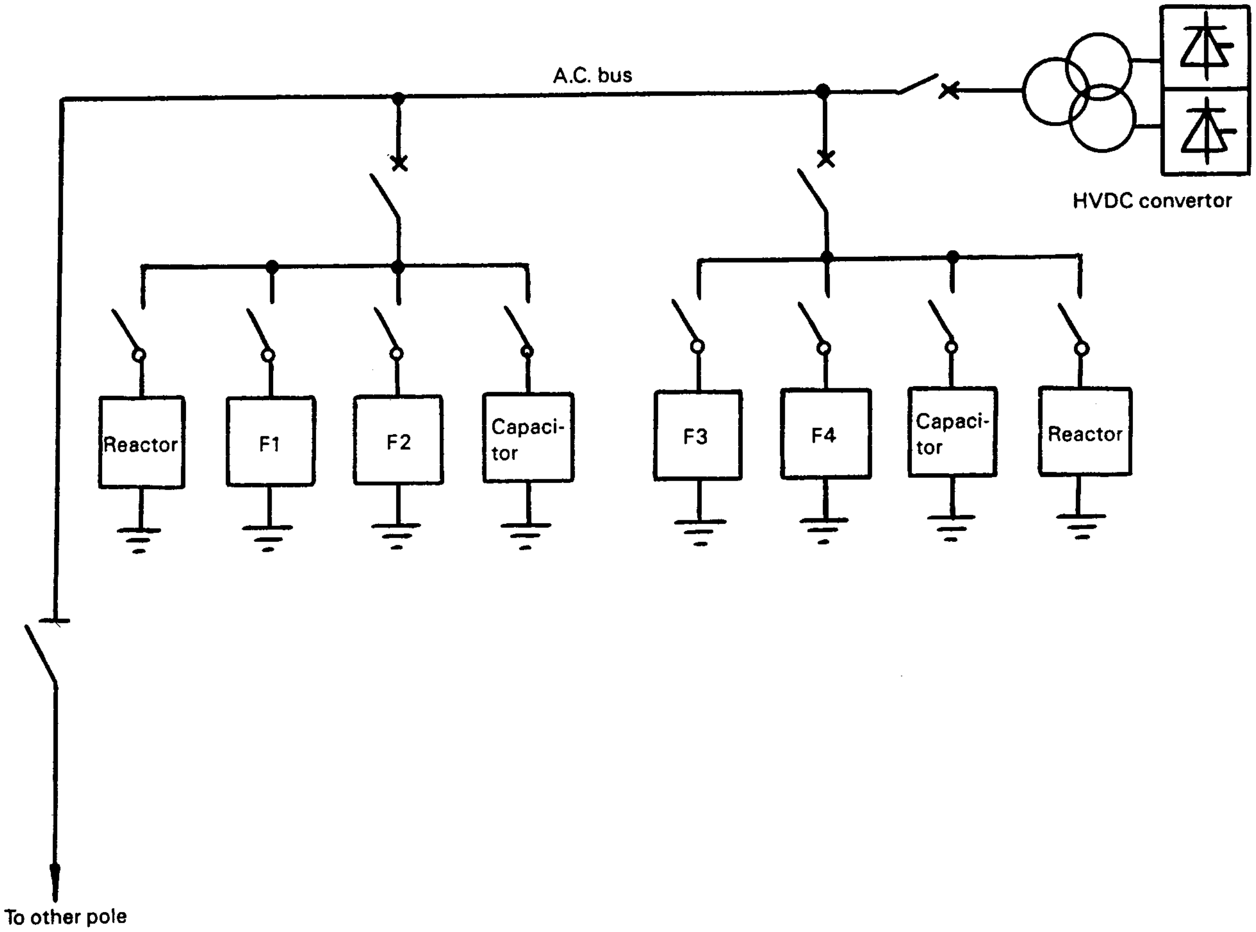


Figure 3 – Example of arrangement of a.c. filters and capacitor and reactor banks for large bipolar HVDC

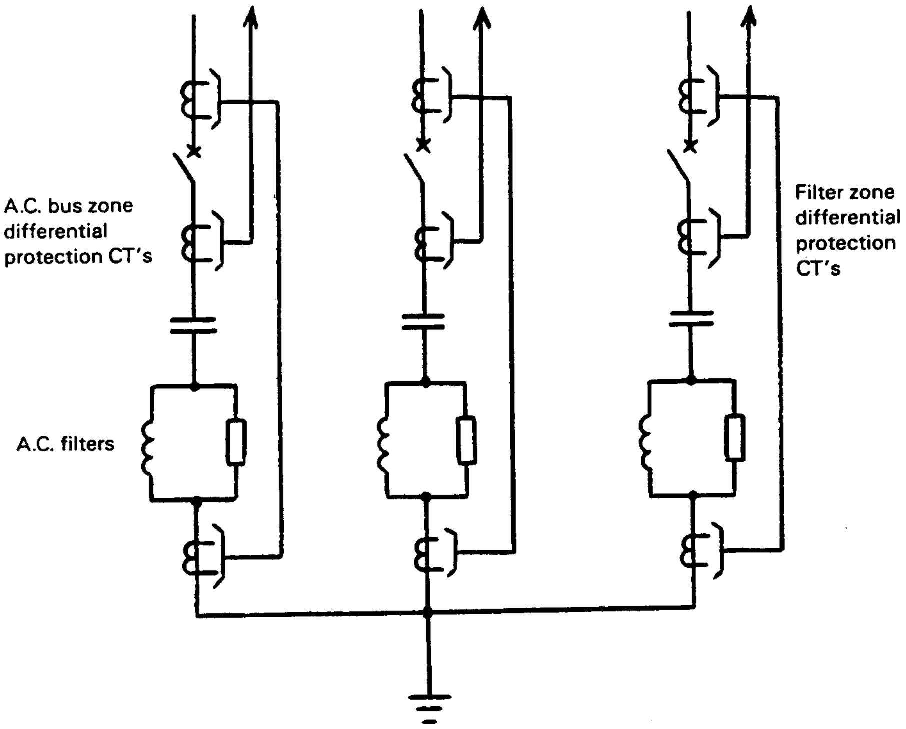

A.C. bus zone differential protection CT's
Filter zone differential protection CT's
A.C. filters

Figure 4 – Example of current transformer arrangements for a.c. filters and a.c. bus differential protections

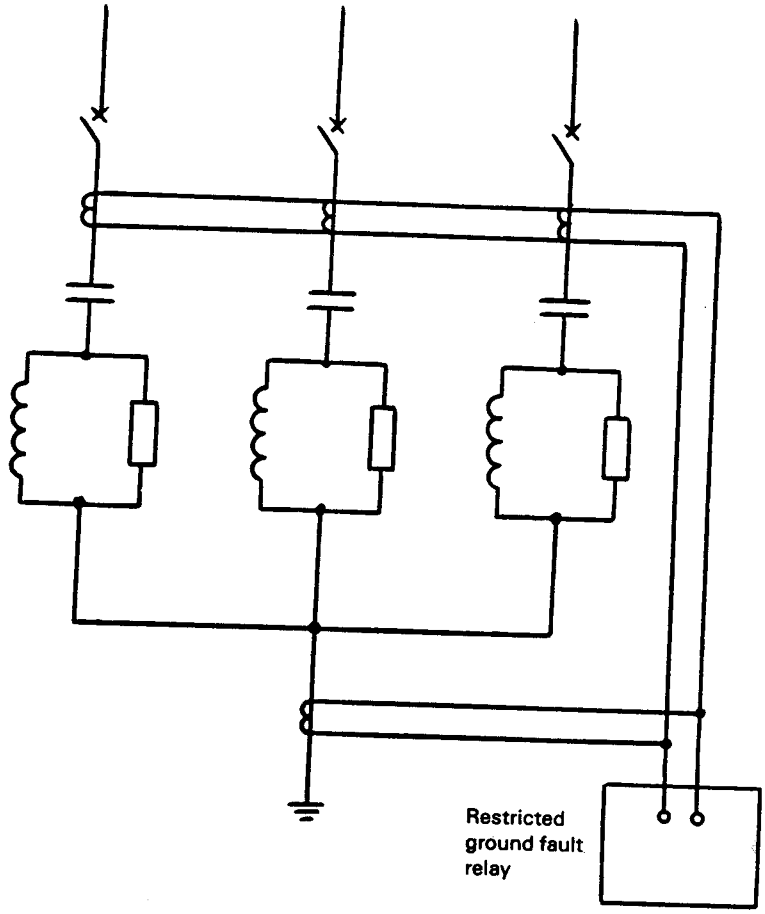


Figure 5 – Example of restricted ground fault protection of filter

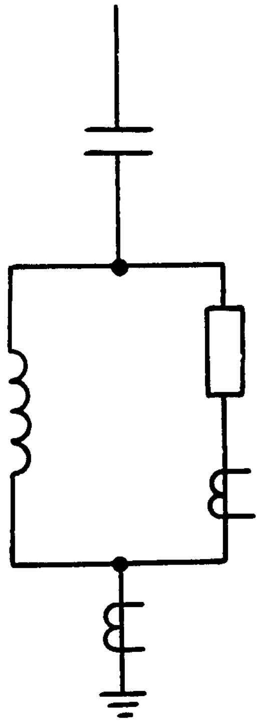


Figure 6 – Example of overload protection of damped filter arm

## 6 Convertor unit faults

### 6.1 *General*

This clause discusses convertor unit faults, i.e., those which take place between the line side of the convertor transformers and the valve side of the smoothing reactor.

Electronic equipment external to the convertor arms but functionally part of them (see IEC 633), is included in the discussion as appropriate. Cooling equipment is discussed in clause 13.

In some applications, convertor units can be connected in series or in parallel on the d.c. side within one pole of the HVDC substation. Fault aspects of such configurations are also addressed.

### 6.2 *Types of convertor unit faults*

Convertor unit faults can be classified as:

1) flashovers or short circuits;
2) failures of the convertor unit to perform its intended function.

### 6.3 *Short circuits*

Short circuits can be caused by breakdown of external or internal insulation, by inadvertent operation of switches or from other causes. They call for a shut-down of the affected convertor unit because of the high probability of equipment damage and the need for repair or replacement.

In bipolar systems or those comprised of two or more independent convertor units per pole, the unaffected convertor units and thus the remainder of the HVDC transmission system can remain operative after a short-circuit in a convertor unit.

For example, figure 7, page 37, shows a number of possible locations of short circuits within a typical convertor unit. Faults within the convertor transformer are not shown since they are not unique to the HVDC application. Figure 7 is valid for each individual convertor unit in parallel or series-connected convertor units.

Usually the most severe fault is a short-circuit of a convertor valve while it is in rectifier operation at minimum delay angle and maximum a.c. voltage, e.g., due to a flashover. This would constitute a near-solid line-to-line short-circuit of the valve side winding of the convertor transformer and subjects the conducting valve in the same commutating group to the fully offset short-circuit current. When the star-star connected transformer is located at the low d.c. voltage side with the d.c. neutral bus solidly grounded, the possibility of a flashover of the transformer neutral to earth also shall be considered.

Other short-circuits on the d.c. side include short-circuits of a six-pulse bridge, of a twelve pulse group or from pole-to-earth. However due to the emf's and the impedances involved in these cases, they impose a somewhat reduced short-circuit current stress on the convertor valves.

Upon detection of a short-circuit, perhaps by the differential protection within an HVDC thyristor valve convertor, common practice requires immediate blocking of all gate pulses to prevent further commutation. The short-circuit current then extinguishes at its first zero crossing, generally within the first cycle following fault initiation. Subsequently the valves are subjected to the recovery voltage including any temporary overvoltages resulting from d.c. load rejection. The a.c. circuit-breaker of the convertor unit is tripped simultaneously as a back-up. Due attention should be given to the breaker for operation under these circumstances because of the possibility of delayed current zero.

Stresses are most severe on the valve that has been carrying the short-circuit current because its thyristors have a higher than normal junction temperature when the recovery voltage is applied. The capability of a thyristor valve to withstand such stresses without damage and to block against the recovery voltage is termed fault suppression capability (see IEC 700).

For any given system, the maximum valve fault current and thus the highest thyristor junction temperature are obtained with the maximum a.c. system fault current level including any contribution from the a.c. filters. On the other hand, the maximum recovery voltage including load rejection overvoltage is in general experienced with the minimum a.c. system fault current level.

Valves should be specified to have fault suppression capability for consistent levels of short-circuit current and recovery voltage. If opening of the convertor unit circuit-breaker is intended to provide back-up for fault suppression capability, the valves should be specified to have survival capability for the time period until the breaker clears.

For faults to earth, including faults 4, 5 and 6 in figure 7, valves not stressed by the fault current can experience fast changes of potential. Depending on circuit parameters, this may subject the convertor valves to stresses equivalent to steep-fronted voltage surges. Specifications then should require that the convertor unit equipment be designed and manufactured to withstand resultant stresses under credible fault conditions, as discussed in the foregoing, without damage.

### 6.4 *Failure of convertor unit to perform its intended function*

The basic function of the convertor unit is to cyclically commutate the direct current between the phases of the a.c. system. To perform this function, two conditions shall be fulfilled: sufficient commutation voltage shall be present; and synchronized cyclical gate pulses shall be generated by the convertor unit control and transmitted to the valve firing circuits.

### 6.4.1 *Rectifier operation*

Usually reduction or distortion of the commutating voltage is of little concern because there is sufficient volt-time area to achieve commutation even for close-in single line-to-earth faults. If the three-phase voltage becomes too low for successful commutation the direct current may be reduced or the convertor may be blocked. When the voltage reappears the convertor should be able to resume operation with the shortest possible delay. This imposes a requirement on valve designs, where auxiliary energy for gating or thyristor protection is taken from the main circuit, in that the electronic circuits should be designed for fast recharging or have adequate energy storage capability.

Persistent failure of a valve to turn on, perhaps due to missing gate pulses, causes the fundamental a.c. voltage to be injected into the d.c. circuit. Depending on circuit parameters, this can lead to transformer saturation, excite possible resonances on the d.c. line, etc. possibly imposing severe stresses on the affected equipment. The specification should require that such faults be detected and appropriate actions taken (see 7.7).

### 6.4.2 *Inverter operation*

During inverter operation the absence of a sufficient commutating voltage-time area or of valve gate pulses results in commutation failure. This subjects the valve to overcurrents and introduces a fundamental a.c. voltage component into the d.c. circuit. Special control strategies such as advancing the delay angle, by-pass pair operation to eliminate fundamental a.c. voltages on the d.c. side, reduction of direct current, etc. are adopted to minimize commutation failures and their effects.

If the commutation failure is caused by insufficient a.c. voltage from an event such as an a.c. system fault (see clause 4), then normal performance can be expected to resume once the fault has been cleared. To avoid shutdown of the convertor, the valves should be designed and manufactured to withstand the stresses resulting from such events for a specified time assisted by the convertor unit control. If the specified time is exceeded or if the commutation failure is caused by missing gate pulses then the convertor should be blocked.

For valve designs where the auxiliary energy required for gating the thyristors is taken from the main circuit, the pertinent electronic circuits should be designed for fast recharging or they should have sufficient energy storage capability so that the convertor can quickly resume normal operation after reappearance of the commutating voltage.

### 6.5 *Convertor unit protection*

Various protective circuits are usually built around the convertor unit to detect faults and operating conditions that can be detrimental to the safety of the equipment, particularly the thyristor valves. The following subclauses list typical circuits some of which can be required only for particular valve designs.

### 6.5.1 *Convertor differential protection*

By comparing the convertor transformer valve side to the direct current, short-circuits within the convertor bridge can be detected. The resulting protective action is to permanently block the convertor unit and trip the associated a.c. circuit-breaker.

### 6.5.2 *Overcurrent protection*

Evaluating the magnitude of the transformer valve side current makes it possible to protect against overload. This also provides backup for convertor differential protection. Protective action is the same as that described in 6.5.1.

### 6.5.3 *A.C. overvoltage protection*

A.C. overvoltage protection can be included by measuring the a.c. voltage, for example at the valve side of the convertor transformer using a capacitive voltage divider as in the transformer bushings or by other means. Protective actions after detecting an undesirable overvoltage might include tripping of capacitor banks, increasing the convertor reactive power consumption, permanent blocking of the valves along with tripping of the convertor unit a.c. circuit-breaker or an appropriate combination of these actions.

### 6.5.4 *Protection against large delay angle operation*

Protection against large delay angle operations can be achieved if required for a particular valve design by measuring the valve delay angles and limiting the duration of such operation in the convertor unit control. The limitation can be made dependent on a.c. voltage and the valve coolant temperatures.

### 6.5.5 *Commutation failure protection*

Commutation failure detection is usually achieved by a.c./d.c. current differential measurement. If recovery does not occur naturally, this acts after some delay to temporarily increase the inverter angle of advance. If no recovery occurs after a further delay, permanent blocking is applied.

### 6.5.6 *Thyristor valve protections*

Thyristor redundancy can be monitored by continuous on-line checking of each thyristor if required. Protective actions can include a warning signal, shut-down and isolation of the convertor unit or a combination of these.

Thyristor forward overvoltage protection can be achieved by monitoring the individual thyristor voltages and applying a gating signal if the safe level is exceeded (see also 11.7.3) or by other means.

Forward recovery protection can be used to protect the thyristors against positive high voltage/time differential $dv/dt$ in the recovery period by applying a gating signal if a safe level is exceeded, or by other means.

### 6.5.7 *Transformer protection*

Convertor transformer protection is the same as conventionally used for transformers in a.c. transmission systems. It includes differential protection, overcurrent protection, gassing or hot spot detection, etc. Protective action is to trip the convertor unit a.c. circuit-breaker. Precautions shall be taken to prevent direct current from flowing in the transformer, for example by bypass-pair operation and thus to assist the circuit-breaker clearing. This can be particularly important for series-connected convertor units.

Operation of overall differential protection for valve side earth faults is complicated due to the absence of a direct earth connection. The effects of harmonics upon the operation of the protection should be considered and in particular in the case of biased differential protection with harmonic restraint.

Special attention should be paid to the design and rating of current transformers used because of possible saturation problems. Problems of concern include for example, injection of direct current in conjunction with commutation failures, neutral bus faults, and delayed neutral bus switch operation (see clause 10).

### 6.5.8 *Transformer tap-changer unbalance protection*

Tap-changer unbalance protection may be required to avoid unbalanced operation of the convertor unit, in turn leading to generation of excessive non-characteristic harmonics. These can overload filters. Protective response is to give an alarm and initiate a manual or automatic tap changer rebalancing procedure.

### 6.5.9 *A.C. connection earth fault protection*

A.C. connection earth fault protection may be used to detect earth faults on the connections between the convertor transformer and the valves (fault 6a and 6b in figure 7, page 37 , when the convertor transformer is energized but the valves are blocked. The valve side voltages of the convertor transformers can be measured by using capacitive voltage dividers in the transformer bushings or the valve hall bushings or by other means. Protective action can be tripping of the convertor unit a.c. circuit-breaker.

### 6.6 *Additional protection aspects of series connected convertor units*

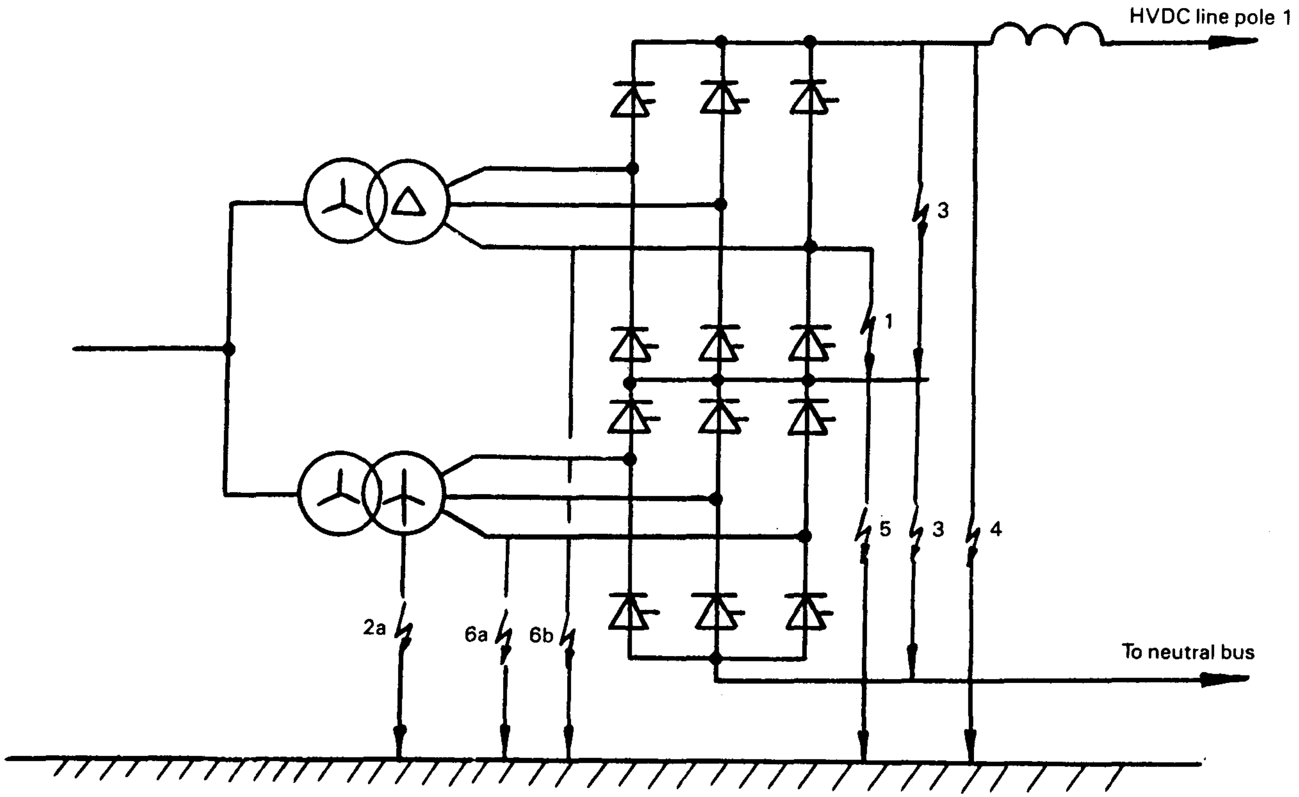
When two or more convertor units are connected in series on the d.c. side within one pole of the HVDC substation, protection for the same types of faults apply as for single convertor units (see 6.3 and 6.4). One additional differential protection, to cover convertor unit faults (type 4 in figure 7), can be included, comparing the current in the high voltage side and in the low voltage side of the convertor unit.

Since both convertor units can be operated independently of each other, subdivision of the convertor portion of the HVDC substation into protection zones should take this into account (see figure 8, page 38). Protective action for short-circuits would generally include blocking of the pole to remove the direct current. If the fault is within the convertor unit 1 or 2 zone, the respective unit then should be isolated and bypassed so that operation can be resumed with the remaining healthy unit. Consideration should also be given to removing one of the convertor units from service at the other end of the transmission system to avoid prolonged operation at large delay angle or angle of advance, respectively.

For certain faults occurring only in one of the series connected convertor units, such as transformer faults or commutation failures, protective sequences can be used in addition to fault removal to divert the direct current from the affected unit by bypass operation of the convertor valves or by closing the bypass switch.

### 6.7 *Additional protection aspects of parallel connected convertor units*

In general, each of the parallel-connected convertor units can be treated independently from the point of view of transient performance and fault protection. However, due consideration should be given to the transient current rating of parallel-connected inverters with respect to commutation failures, especially if the inverters have differing steady-state current ratings. D.C. breakers may be desirable at the pole bus (figure 9, page 38), for isolation of faulty convertor units, especially inverters, to avoid the need to temporarily block the complete transmission pole.



**Fault list**

1: Short-circuit of valve

2a: Earth or ground fault of the star point of the star-connected transformer windings at the valve side of the bridge near to ground

2b: Earth or ground fault of the star point of the star-connected transformer windings at the valve side of the bridge far from ground

3: Short-circuit of the bridge

4: Earth or ground fault of the twelve-pulse convertor unit bus

5: Earth or ground fault of the midpoint d.c. bus

6a: Earth or ground fault of the a.c. connection of the bridge near to ground

6b: Earth or ground fault of the a.c. connection of the bridge far from ground

Figure 7 – Examples of faults in a twelve-pulse convertor unit

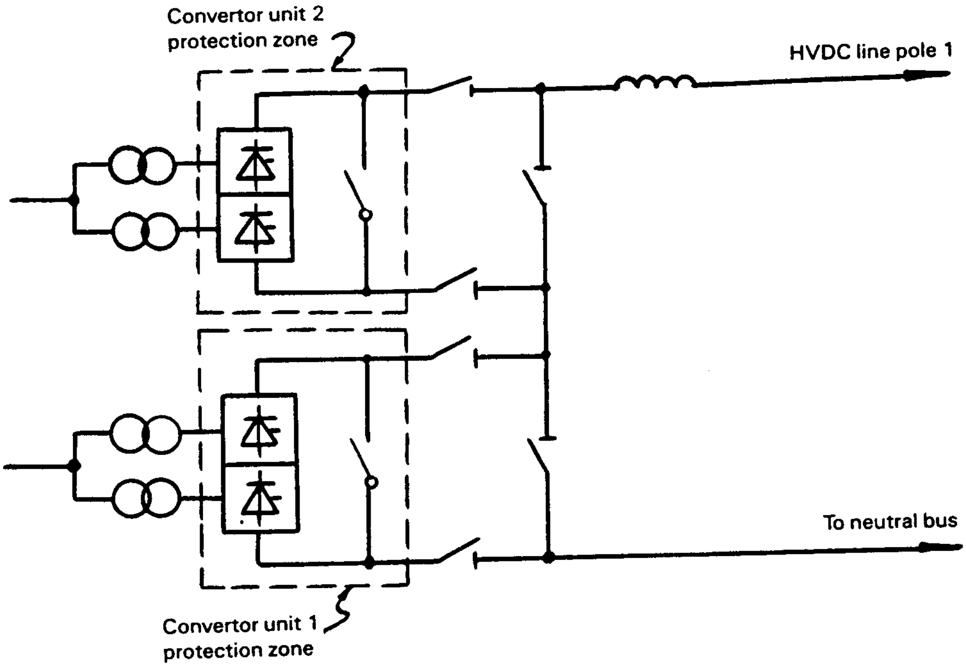


Figure 8 – Protection zones in series-connected convertor units

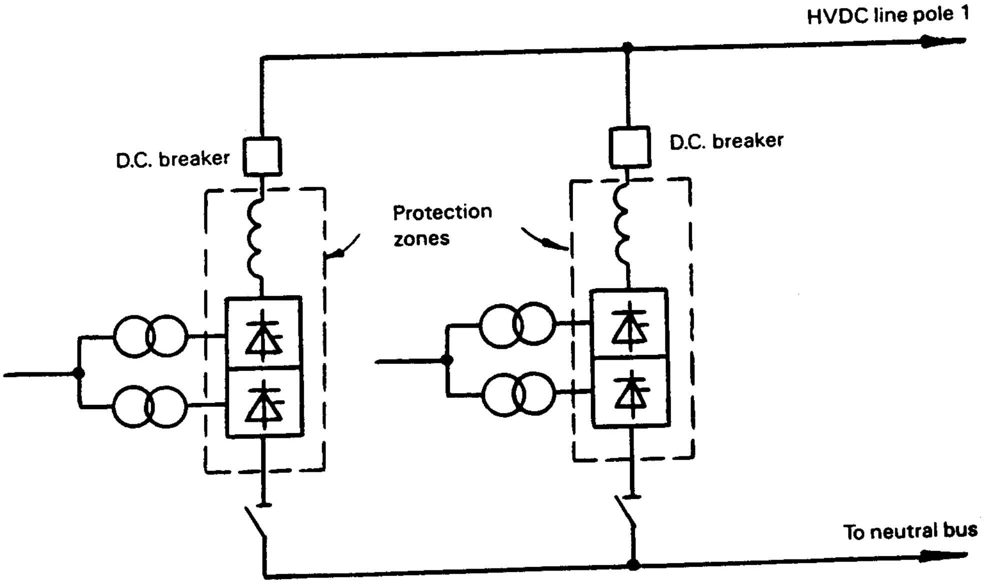


Figure 9 – Protection zones in parallel-connected convertor units

## 7 D.C. reactor, d.c. filter and other d.c. equipment faults

### 7.1 *General*

This clause discusses faults in the HVDC substation for an HVDC transmission system bounded by:

1) the valve side of the d.c. reactor to the d.c. transmission line in each pole;

2) from the neutral side of the convertor unit for each pole to the earth electrode line.

### 7.2 *Fault types*

Types of faults that should be considered for the protection of the d.c. side equipments and bus sections include:

1) bus-to-earth and bus-to-bus faults;
2) equipment faults;
3) failure of d.c. switching devices to perform their intended switching functions.

### 7.3 *Protection zones*

Specifications for HVDC substations should make provision not only for the protection of all d.c. side equipments, but also for the co-ordination of protections.

In HVDC systems the zone protection philosophy and techniques of implementation to achieve zones of protection are in general much the same as with a.c. protection practices. However, in HVDC systems the fault suppression capability of the convertor valves (see clause 6), in addition to the relatively high impedance of d.c. reactors and transformers aids in achieving protection selectively on the d.c. side.

Protection zones of an HVDC substation should be arranged such that all equipment is fully protected by at least one protective function within the HVDC substation.

A communication system between substations of the HVDC transmission can be used to optimize recovery from faults and to improve fault protection selectivity for many faults which can take place on an HVDC transmission system. However it should not be necessary for protection of the equipment under discussion in this clause. Figures 10 and 11, pages 44 and 45, show examples of HVDC protection zones and measuring devices for two configurations of HVDC substations.

### 7.4 *Neutral protection*

In an HVDC system the neutral side protection is generally divided into zones that enable independent fault detection plus selective isolation by pole and a protective zone common to both poles. The latter requires a bipole shutdown to provide corrective maintenance.

### 7.4.1 *Neutral fault detection*

In a bipolar configuration operating under balanced conditions, the pole neutral protection zone, the bipole neutral protection zone and the earth electrode line protection zone (see clause 9) are all essentially at earth potential. An earth fault in any of these zones would therefore not interfere with station operation under balanced bipolar conditions. Any d.c. fault current then would be practically zero.

Faults to earth in these neutral zones would be detectable whenever the poles of the bipole are temporarily unbalanced for any reason such as during startup, shutdown or disturbance on one pole. The HVDC specifications should consider use only of neutral zone alarms if the operation of both poles is expected to be reasonably balanced. This would allow operator decision on corrective actions to be taken based on safety considerations and the power transmission requirements at the time of fault detection.

The pole neutral and bipole neutral zones should be bounded by d.c. current transformers (d.c.-c.t.). A fault within the respective zones can be detected by a differential comparison of the currents as measured by the d.c.-c.t.'s at the zone boundaries during an unbalance operating condition between the two poles.

### 7.4.2 *Neutral bus fault isolation*

Faults to earth within the neutral zone or convertor zone require a permanent stop of the pole for correction of the faulted condition.

The neutral bus switching device is utilized during the protection sequence to isolate the faulted pole and to transfer any residual pole current to earth return.

Current transfer requirements of the neutral bus switching device should consider the most onerous condition up to and including maximum healthy pole current and location of faults. The switch shall be capable of developing a voltage greater than the IR drop of the earth return to force the current transfer. For systems in which either earth return or on-line transfer to metallic return are not permitted, load break capability of the switching device may not be needed. In this case, a disconnector would be adequate.

In addition, the failure to open the neutral bus switching device of one of the poles will cause a bipole blocking.

### 7.4.3 *Bipolar neutral bus faults*

Bus faults within the bipolar neutral protection zone are detectable by differential comparison schemes such as discussed in 7.4.1. A neutral bus fault in this zone requires a bipole shutdown to provide corrective maintenance which could be a scheduled shutdown.

### 7.5 *D.C. reactor protection*

The d.c. reactors of each pole can be either oil-insulated or dry type. Protection of oil type reactors utilizes many of the same techniques as are applied to a.c. transformers with due consideration to the fact that direct current quantities are involved in the operation of the protective devices.

Protection can include:

- pressure relief devices;
- oil temperature monitoring;
- oil level monitoring;
- gas sensing;
- winding temperature sensing;
- loss of cooling detection;
- differential protection.

Differential protection can be specified around the d.c. reactors or these equipments can be included in one of the HVDC substation protection zones as shown in figures 10 and 11, pages 44 and 45.

Oil type d.c. reactor bushing designs lend themselves to an economic solution to the problem of housing the d.c.-c.t.'s required for differential protection.

When dry type d.c. reactors are employed, separately mounted d.c.-c.t.'s will be needed for reactor fault detection.

### 7.6 *D.C. harmonic filter protection*

The d.c. filters associated with HVDC substations are normally specified to limit harmonic interference caused by harmonic currents flowing into the d.c. line (see IEC 919–1, section seventeen).

Protection design for the d.c. filter arms should take into account the full range of normal and abnormal operating conditions which should be specified for the HVDC substations.

Similarly the protection design for the d.c. filter elements, such as capacitors, reactors, damping resistors, and disconnectors shall consider all expected operational conditions that result in filter elements being overstressed due to harmonic currents which for example can result from operation at large delay angles, angles of advance or from resonant conditions, etc.

#### 7.6.1 *Filter bank fault protection*

D.C. filter capacitor bank faults to earth can activate the d.c. line pole protection. However the specifications should require that d.c. line protection operation should not prevent correct identification of any d.c. filter faults and should automatically initiate clearing and isolation of the faulted filter branch.

Any fault within the d.c. filter zone may be detected by a differential comparison between the d.c.-c.t.'s at the boundary of the line side d.c. substation zone as shown in figures 10 and 11. Other equipment such as line traps, coupling capacitors, d.c. voltage dividers, etc. can also be included in this zone of protection.

Isolation of a faulted filter may require temporary blocking of the affected pole to permit disconnector operation.

If operation is to continue after removal of the faulted d.c. filter branch, the specification should consider the increased d.c. side interference levels expected, possible overloading of other filters and potential resonant conditions.

### 7.6.2 *D.C. filter capacitor unit protection*

Since capacitor banks associated with the d.c. filters normally consist of a combination of series and parallel elements, a variety of protection philosophies may be applied, namely:

- fuse protection (internal or external) if the fuses do provide useful protection;
- unbalance protection within a capacitor bank;
- monitoring of the state of filter tuning by on-line or off-line measurements to locate failures;
- visual or remote indication of failed units or voltage level from earth;
- separate failure alarms to indicate non-critical and critical levels of capacitor failures, including automatic removal of the filter arm if continued operation could result in an avalanche of capacitor failures.

### 7.7 *D.C. harmonic protection*

Protection against fundamental and harmonic frequency components on the d.c. side should be considered in the specification of any HVDC system. Fundamental frequency components on the d.c. side lead to a d.c. and second harmonic frequency component on the a.c. side which can cause transformer saturation or resonant conditions. The fundamental frequency can be detected in the voltage divider or d.c.-c.t. signals. The related harmonic protection normally initiates pole blocking whenever the harmonic component exceeds a given threshold value for a specified time.

### 7.8 *D.C. overvoltage protection*

Specifications for HVDC substations should consider d.c. side overvoltage protection to assure that all equipments and the d.c. line or cable are protected against steady-state overvoltages. Transient overvoltage protection can be addressed as part of the arrester co-ordination (see clause 11). Normally convertor controls are utilized to implement d.c. system steady state overvoltage protection functions.

### 7.9 *D.C. side switching protection*

Switching devices such as high speed pole circuit-breakers and d.c. side disconnectors, including d.c. filter and pole disconnectors, shall be covered in the specifications. Specification of these switching devices shall consider current interrupting or commutation capability. In addition, permissible switch arcing time without unacceptable equipment damage shall be considered.

The disconnectors usually operate at no-load and their operating supervision should be provided either by the equipment or by other associated protection. The on-load switches, such as the by-pass breakers, should have a dedicated protection.

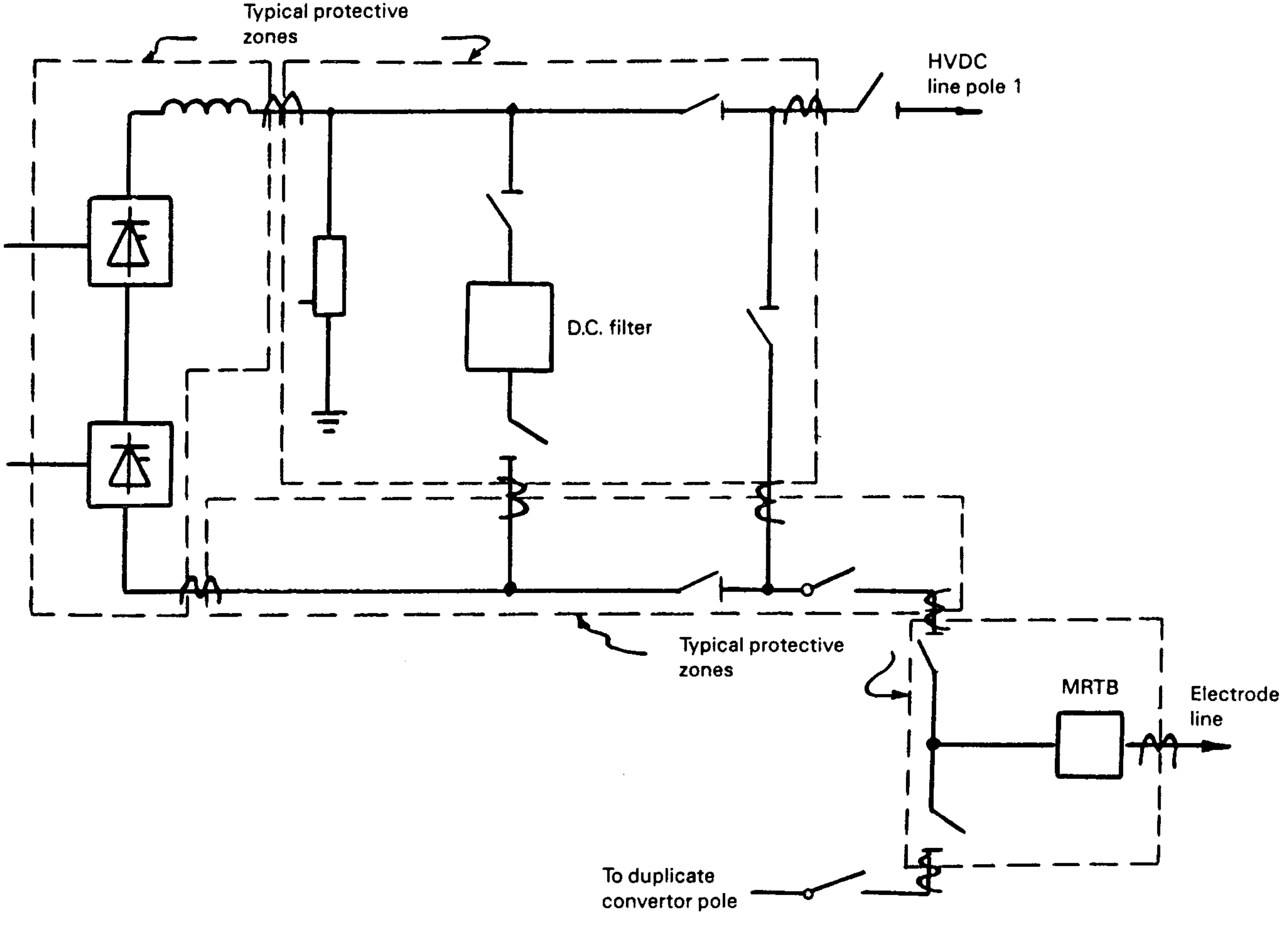


Figure 10 – Example of d.c. protection zones

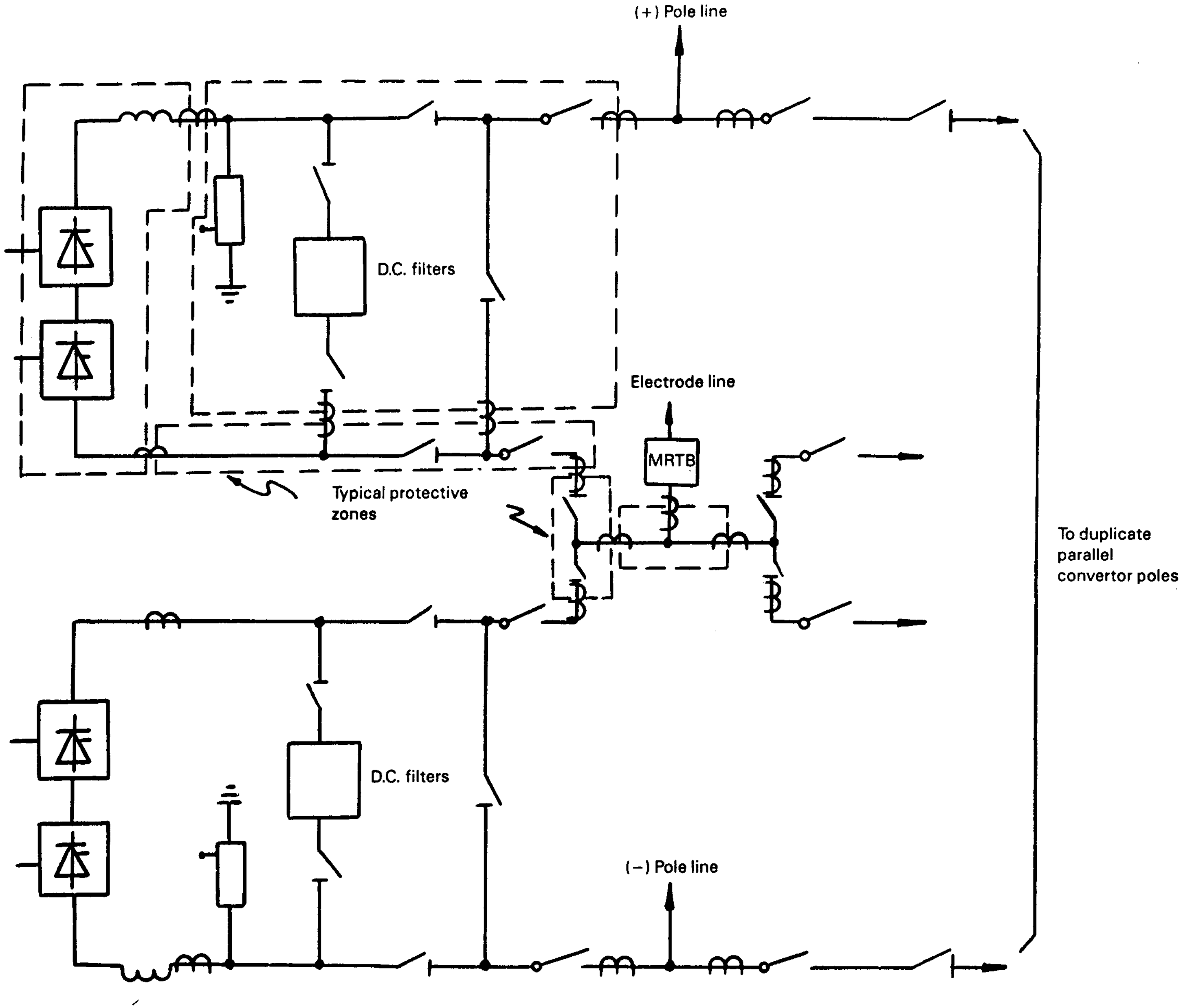


Figure 11 – Example of d.c. protection zones for parallel-connected convertor poles

## 8 D.C. line faults

### 8.1 *Overhead line faults*

An overhead line, particularly if it is very long, may be a source of major disturbances in an HVDC transmission system. The most common fault on an overhead line is a flashover between a line pole and earth. If the line is bipolar the conductors of the two line poles are most often arranged at such a distance from each other that a flashover between poles is excluded for practical purposes.

Overhead line faults are mainly caused by:

- lightning strokes;
- contamination by: salt, industrial pollutants, sand and dust, etc.;
- overvoltages due to faults, control system malfunction, etc.;

- fallen towers;
- other: snow or ice damage, wind, bush fires, tree contacts, etc.

Most d.c. line faults are temporary, i.e. the insulation at the fault location is nearly always restored to its pre-fault level after the fault is cleared. Also since the d.c. fault current is relatively low, it does not usually cause appreciable damage to the conductors and insulators of the line. These considerations mean that in most cases faulted d.c. lines may be restored to service quickly.

For design of an overhead d.c. transmission line the insulation strength of the line against lightning, switching surges, and contamination is selected so that the probability of a single fault to earth is limited to an acceptably low level. Moreover the design should seek to prevent faults to earth due to overvoltages such as those which appear on the healthy pole during a pole-to-earth fault on the opposite pole or those resulting from commutation failure.

In addition to the above line design considerations, the magnitude of overvoltages due to commutation failure, complete loss of valve control pulses, or energization of a d.c. line with the remote terminal open can be limited by proper design of the control system.

The probability that a bipole outage will be caused by lightning or from a single pole-to-earth fault is low.

During d.c. line single pole-to-earth faults, power flow on the faulty pole is temporarily interrupted and a transient overvoltage appears on the healthy pole, d.c. filters, d.c. reactors and metallic return line or the earth electrode line.

### 8.2 *Cable faults*

Underwater cable faults are the result of mechanical damage by anchoring and trawling, by degradation of cable insulation, or by unexpected overvoltages. Characteristically, cable faults are not self-healing so that a lengthy outage follows for cable repair or replacement.

### 8.3 *D.C. fault characteristics*

In addition to being essentially unidirectional instead of sinusoidal as in a.c. systems, fault current in a d.c. line is caused to vary by control action in a quite different manner than for a.c. line faults. Initially the rectifier current increases and then after a short time is returned to the preset value or to a lower level as determined by the voltage dependent control action of the rectifier current controller or by other control action. The fault current will continue to flow until it is cleared by control action.

When a d.c. line fault occurs the d.c. voltage for the faulted pole or poles is reduced suddenly to a low level. On the line side of the d.c. reactor, the rate of change of the voltage, $dv/dt$, is larger than that produced by a commutation failure or by a d.c. bridge fault. These two phenomena, i.e. reduction in pole voltage to a low level and high $dv/dt$ are important for d.c. line protection.

### 8.4 *Functional d.c. fault detection requirements*

D.C. line faults can be detected by utilizing the characteristics of the d.c. side currents and voltages. Detection systems should provide that:

- primary detection be fast;
- detection should be insensitive to normal transient operating conditions such as low voltage operations, system startup and shutdown, power reversal, etc.;

- detection should be insensitive to convertor and a.c. system faults but can be actuated by d.c. bus faults;
- in a combined overhead line and cable system, means should be considered for identification of the faulted section;
- in a parallel transmission line system, fault detection should be selective so that the faulted line can be quickly identified.

Fault locators can be utilized to expedite inspection and maintenance of the faulted line.

### 8.5 *Protective sequence*

The d.c. protection system should be designed and operated to reduce line outage times due to line faults to a minimum.

### 8.5.1 *Overhead line faults*

Those overhead line faults which are caused by lightning strokes are usually not permanent. When such a d.c. line fault is detected, the fault current is reduced to zero by control action. Inverter backfeed into the fault must be prevented by proper design of the inverter's control system.

Following the reduction to zero fault current, a dead time should be provided to allow for deionization of the fault path prior to re-application of voltage and restoration of the faulted line pole to service.

The required dead time is a function of fault current, system voltage, climatic conditions and type of system i.e. monopolar or bipolar. Typical dead time allowance on d.c. overhead transmission lines are in the range 100 ms to 500 ms.

If the first attempt at restart is unsuccessful, additional restart attempts can be made. If so, progressively longer dead times or restart at a lower d.c. voltage would be appropriate to enhance the possibility of a successful restart. The latter option would be particularly attractive if the line insulation is partially damaged at the fault location, or if polluted conditions of a section of the line will not permit operation of the line at full voltage and it is important to continue transmission of power even at reduced capacity.

### 8.5.2 *Faults in cable systems*

The cable insulation at the fault location is not self-healing or self-restoring after the fault has been cleared. The current in the faulted pole should be reduced to zero and the convertors blocked for cable faults.

### 8.5.3 *Faults in an overhead line/cable system*

Identification of whether the fault is in the overhead or cable section of the line is needed only if restart attempts are not to be made for faults in the cable section.

### 8.5.4 *Faults in one of a system of parallel-connected cables*

When a fault is detected the faulted cable should be identified and the current in the faulted pole should be reduced to zero as quickly as possible. The faulty cable then should be disconnected and the system restarted using the remaining healthy cable(s).

If a d.c. circuit-breaker with enough current interruption and recovery voltage capability is used in each cable path, it is only necessary to open the d.c. circuit-breakers at both ends of the faulted cable without having to force the pole current to zero. Use of d.c. circuit-breakers in this manner can improve system restoration times.

### 8.5.5 *Fault in a system of parallel overhead lines*

The faulted overhead line should be identified and the current in the fault reduced to zero as described above. The restart sequence at full voltage should then be performed. If restart fails, the usual strategy is to leave the pole current at zero and disconnect the faulty line after which the d.c. system can after be restarted. If d.c. circuit-breakers with suitable relaying systems are utilized in each line, the faulted line can be disconnected without forcing the pole current to zero.

### 8.6 *Fault protection schemes*

Fault protection for d.c. lines is usually based on measurements of d*v*/d*t* and the d.c. voltage. The use of these two measurements means that usually there is no need for exchange of information between the two line terminals for fault detection and clearing and system restart. However telecommunication may be required between the two HVDC substations for some specific applications and fault conditions.

When a d.c. line fault takes place close to the inverter end, the d.c. voltage level protection at the rectifier end may not achieve line fault clearing as reliably or as quickly as required. Telecommunication from the inverter to the rectifier end may then be necessary to assure fast actuation of the retard function at the rectifier to reduce the current to zero and allow deionization of the fault path followed by re-energization of the faulted line.

Detection of high resistance d.c. line faults or the specified fault clearing times cannot always be achievable using the above protection schemes. In this event, some type of differential current detector arrangement may be needed. This would use telecommunication channels in both directions to allow comparison of the d.c. current at the rectifier and inverter ends of the d.c. line. An alternative approach might be to wait for the fault to develop into a low impedance fault which would then be detected by one of the first two methods described above.

The d.c. transmission line protection cannot always discriminate between blocking and bypassing of the inverter or d.c. line faults. To remedy this weakness and allow for proper discrimination a telecommunication channel from the inverter to the rectifier could be applied to inhibit the line fault protection when the inverter is blocked.

The d.c. transmission line protection, based on voltage level, can misoperate for faults on the a.c. side of the inverter or because of persistent inverter commutation failures. Again, a telecommunication channel may be needed between the inverter and the rectifier to allow the line fault protection to be inhibited under these conditions.

When two d.c. lines are operated in parallel and an automatic line switching sequence is used, telecommunication channels are normally required in both directions between the rectifier and inverter, in order to permit d.c. line isolation sequencing following a fault on one line. If d.c. circuit-breakers with full recovery voltage capability are used to switch the d.c. lines, telecommunication channels would no longer be necessary provided suitable relaying is available to identify the faulted line.

Similarly, telecommunication channels are normally required in both directions between the rectifier and inverter on a per pole basis, where automatic paralleling and deparalleling of poles is to be used after a permanent fault on one of the d.c. lines.

### 8.7 *Open circuit on the d.c. side*

Overvoltage may result if a rectifier is started into an open-circuited d.c. pole or a blocked inverter unless appropriate control action is included in the design.

When a restart attempt is made into an open-circuited earth electrode line or neutral conductor the current will be forced through a neutral arrester. Inadvertent opening of the neutral bus switching device also can have the same result. High speed arrester shorting switches can be used to protect this arrester. Provision should be made in the protection system for the detection of these conditions.

### 8.8 *Power line cross protection*

When d.c. and a.c. transmission lines cross over one another, there is a risk that the two may come in contact due to collapse of a transmission tower or broken suspension insulators, for example. This undesirable condition is detected by several protections in the HVDC system, normally applied for other purposes. The fastest is d.c. line fault detection, others are d.c. undervoltage detection, and fundamental frequency detection. These block the HVDC but can leave the d.c. conductor energized from the a.c. line. A.C. line protections may not operate for this condition because of the relatively low current in the fault. Therefore, usually it will be desirable to trip the a.c. line from the appropriate HVDC protection relays.

## 9 Earth electrode line faults

### 9.1 *General*

The earth electrode line is an important part of a d.c. transmission system. It is common to both poles and a fault on the electrode line could seriously influence the HVDC bipole availability. If monopolar operation with earth return is required, the earth electrode line is an essential item of the HVDC transmission system.

The electrode line can be constructed using the d.c. line structures either to support its conductor(s) or by using the conductor to serve as a shield wire. In the latter case it should be insulated. A technically superior alternative is to build an entirely separate electrode line, as uncoupled as possible from the main d.c. transmission line.

### 9.2 *Specific requirements - Earth electrode line*

The electrode line design should minimize the occurrence of permanent faults. In support of this design objective, the following practices are desirable:

- to avoid permanent faults on the electrode line its insulation should be designed so that transient faults resulting from direct or induced lightning surges will tend to be self-extinguishing;
- there should be no flashover across the electrode line insulation under the voltages induced on the earth electrode line during faults on the main d.c. line;
- if it is impossible or impractical to avoid these flashovers, flashover arcs should self-extinguish;
- if the electrode line is constructed separate from the main d.c. line, the risk of insulation flashover is minimized; in any case, arcing horns can be effective in achieving arc self-extinguishment;
- the mechanical design should avoid the possibility of an open circuit in the earth electrode line; one way to achieve this objective would be to use two parallel conductors each supported by an independent insulator string; this will diminish the possibility of an open circuit and offers opportunity to monitor the line by means of a transversal differential protective scheme for comparing the currents in the two conductors for detection of electrode line faults or an open conductor (one of the two conductors);
- the earthing resistance of the electrode line structures should be low for best lightning performance and easier fault detection. However to achieve arc self-extinguishment the tower footing resistance should not be too low, bearing in mind that this may impinge on safety.

### 9.3 *Electrode line supervision*

For safety reasons provision may have to be made to recognize a permanently faulted or open earth electrode line. Such a system could give an alarm or order a blocking sequence for the bipole involved. For transient or temporary faults usually no action from the alarm and monitoring will be required.

Implementation of such a supervision system can be based on an impedance monitoring principle either by using the d.c. current, or by additional means. It should be borne in mind that using the direct current is feasible only if the HVDC system operates with unbalanced d.c. pole current. Other methods have been proposed to overcome this problem.

## 10 Metallic return conductor faults

### 10.1 *Conductor for the return circuit*

If metallic return is used during monopolar operation of a bipolar HVDC transmission either a low voltage dedicated conductor (figure 12, page 55 ), which can be the HVDC line shield wire appropriately insulated, or a high voltage conductor of the other pole, which is temporarily out of service, can be used for the return circuit (figure 13, page 55 ).

The insulation level for the dedicated conductor can be low as it is normally stressed only by the line voltage drop. Switching devices should be provided to transfer the circuit from earth return to metallic return and vice versa when the pole conductor is used for the metallic return. Requirements for the switching devices would depend mainly on whether the transfers are to be executed on-load or off-load.

### 10.2 *Metallic return faults*

Conductor faults on the return circuit will have similar causes to those described in clause 8. When using a low voltage insulated conductor the number of earth fault occasions can be expected to be large because even an induced lightning surge can break down the lower level insulation. On the other hand the number of flashovers should be much smaller when using the pole conductor for metallic return because of its inherently greater insulation.

Fault current will be distributed in the different return paths in inverse proportion to their resistances as determined by the following factors:

- earth fault location on the line;
- arc resistance;
- soil resistivity;
- tower footing resistance;
- resistance to remote earth at the earthing end (station ground mat or the earth electrode).

If the station ground mat is used for the main d.c. circuit earthing during metallic return operations, a portion of the direct current from earth faults can flow into the a.c. system through power transformer earthed neutrals (see figure 14, page 56 ).

Protective relays in the a.c. system then may malfunction due to saturation effects in the power transformers and in the current transformers when the direct current flowing into the a.c. system is large enough and sustained. Therefore it is particularly important that any metallic return earth faults be cleared rapidly to mitigate this problem.

On low voltage return circuit conductors arcing horns capable of clearing earth faults by self-extinguishing or other equally effective means should be provided so that arc damage to the conductor and insulators will be minimal.

An open circuit return conductor fault can cause severe overvoltage at the floating end. A protective relay which will detect this fault as for the electrode line shall be provided for the return circuit together with overvoltage protection.

### 10.3 *Fault detection - Metallic return*

During balanced bipolar operation, faults on metallic return conductors are difficult to detect because of the resulting small changes in voltage and current in the main circuits.

However in monopolar or unbalanced bipolar operation a metallic return conductor fault can be detected through changes in current, which can be used for fault sensing. For example the direct current will flow into the earthing point of the main circuit and the current in the metallic return conductor can be expected to decrease.

Metallic return fault detection examples are illustrated in the following schemes:

- to detect a larger current in the main circuit than in the return circuit (see figure 15, page 57);
- to detect direct current at the grounding point of the main circuit (see figure 15);
- to detect change in alternating current signal superimposed on the return circuit by the a.c. auxiliary power source (see figure 16, page 58).

To shorten the expedited inspection and maintenance time after the faults, a fault locator on the return circuit would be highly desirable.

Detection of an open circuit return conductor should also be considered in the protection scheme.

### 10.4 *Metallic return fault protection systems*

Usually, during balanced bipolar operations it is not necessary to initiate protective sequences for metallic return conductor faults as all of them except permanent and open-circuit faults can be cleared by self-extinguishing actions.

However in monopolar and unbalanced bipolar operations, fault clearing by the main d.c. line protection can be required. Under these modes of operation metallic return fault currents can persist for some time (up to 0,5 seconds), depending on the location of the fault, its current and gap length and wind conditions. Faults near the earthing point can be expected to extinguish rapidly while remote faults will take longer. The self-extinguishing capability of arcing horns becomes more difficult for those faults more distant from the earthed end.

An alternative protection against undesirable long lasting arcs and repeated block-restarts due to frequent faults on the metallic return conductor as can often occur on a low voltage insulated conductor might be considered should the need arise:

- Extinguishing of the arc at a fault without blocking of the convertors can be accomplished by closing the d.c. circuit-breaker (MRTB) installed at the floating end for a short time so that the main circuit is earthed at both ends (see figure 17, page 58).

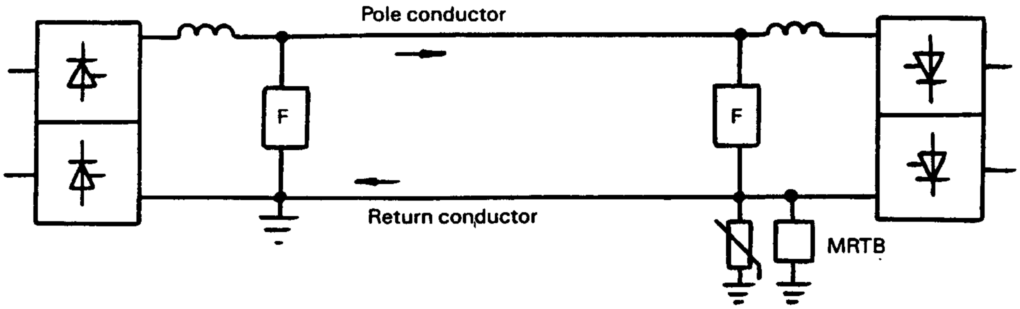


Figure 12 – Monopolar metallic return system showing Metallic Return Transfer Breaker (MRTB)

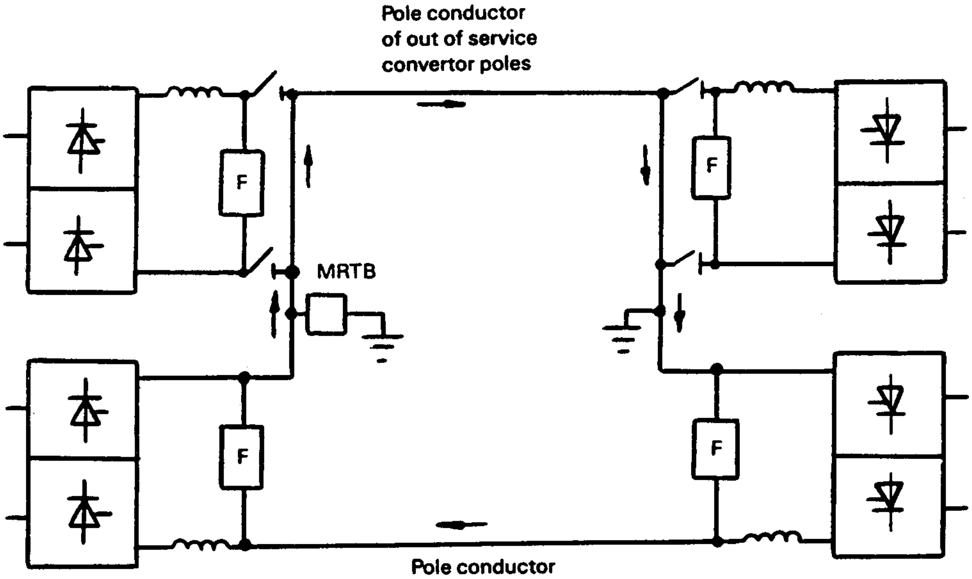


Figure 13 – Monopolar operation of a bipolar system during convertor pole outages

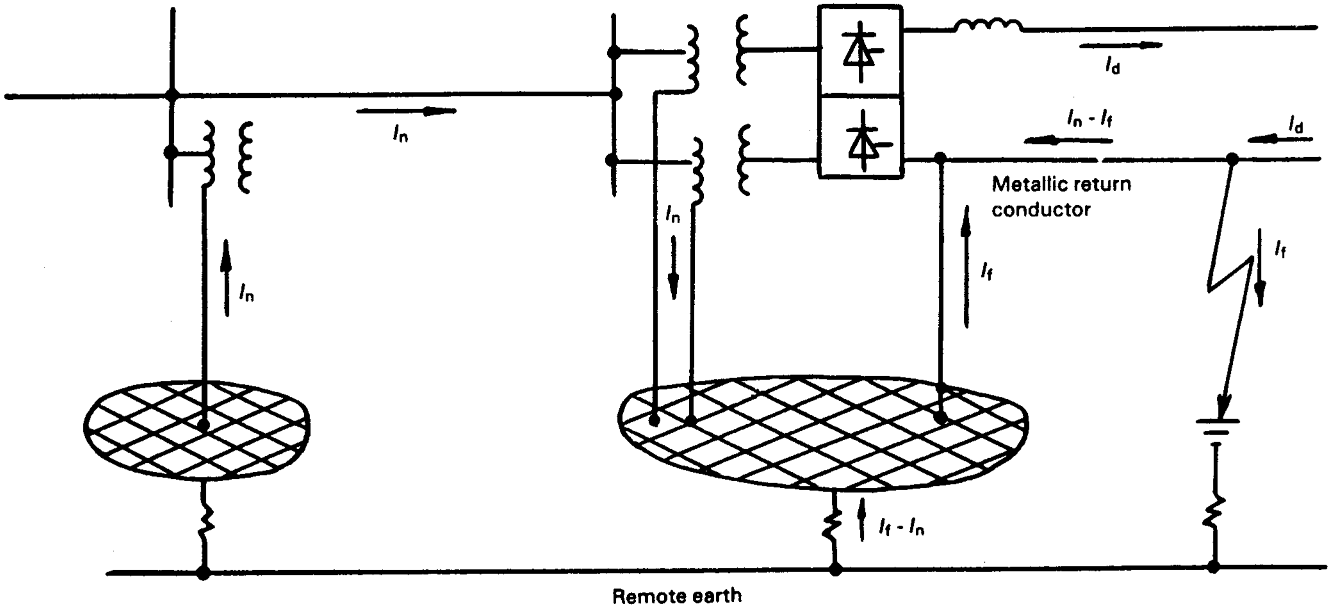


Figure 14 – D.C. current flowing into an a.c. system during a fault on a metallic return conductor when the HVDC substation ground mat is used for grounding of the d.c. circuit

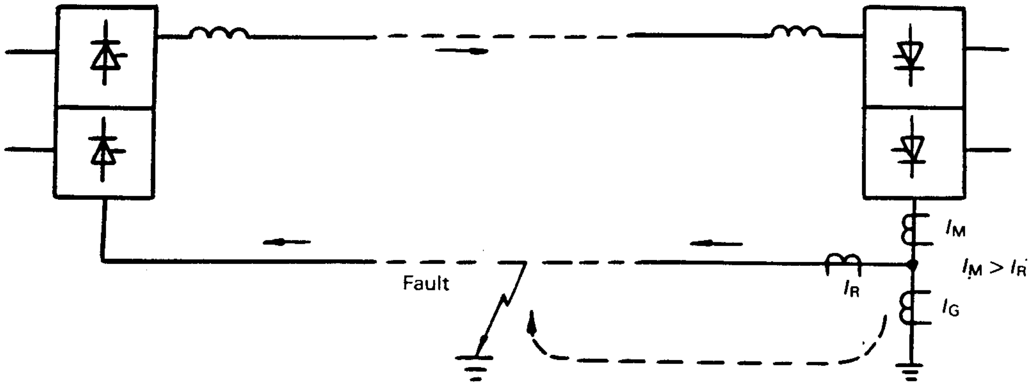


**Figure 15a – Metallic return conductor fault to earth**

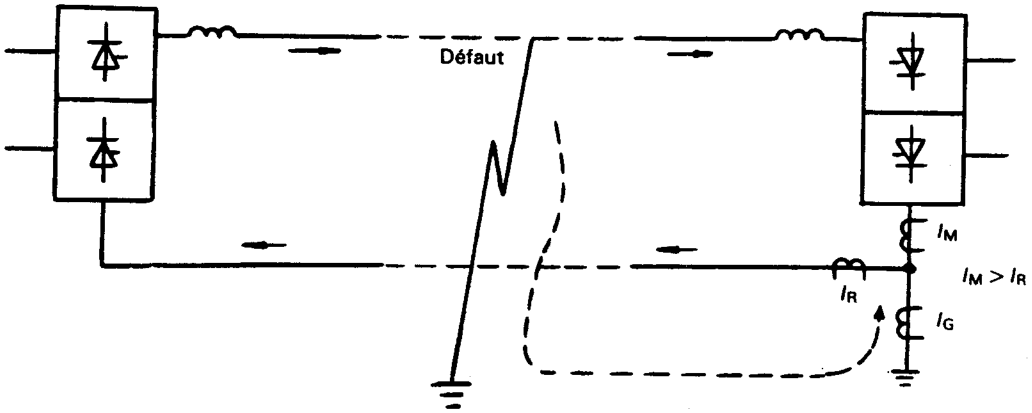


**Figure 15b – Main conductor fault to earth**

$I_M$ is the current in main conductor
$I_R$ is the current in return conductor

**Figure 15 – Earth current flowing during line faults**

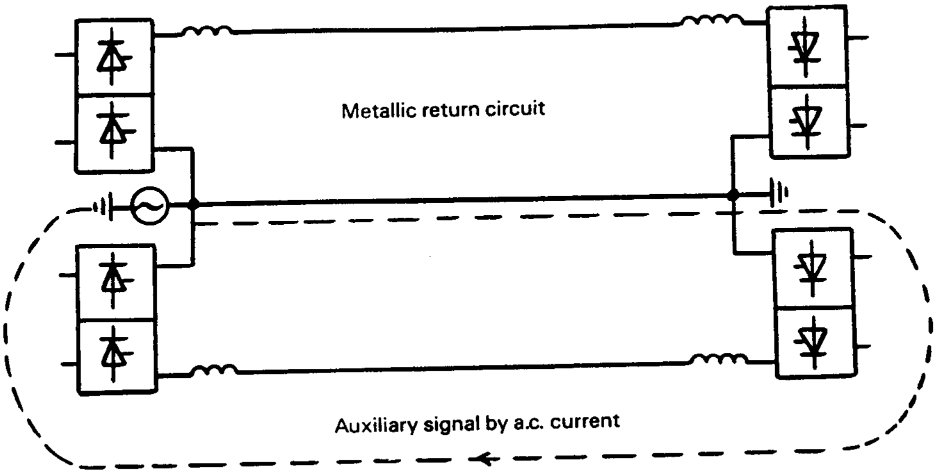


Figure 16 – Example of metallic return fault detection system by means of auxiliary a.c. signal

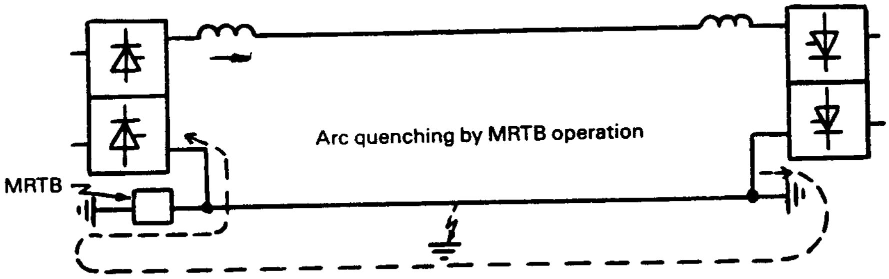


Figure 17 – Example of use of MRTB to quench fault to earth on metallic return conductor

## 11 Insulation co-ordination – HVDC systems

### 11.1 *General*

HVDC substation equipment should be designed to withstand without damage overvoltages that may result from events in the a.c. system or the d.c. line or from malfunctions of the convertor equipment.

Insulation co-ordination of an HVDC substation differs from that of a normal a.c. substation, primarily in the need to consider the requirements of series connected equipment involving arresters connected between terminals away from earth potential, and in the use of different insulation levels for different parts of the substation.

The characteristics of the convertor valves, including the control of their firing instants, and the installation of very large filters on both the a.c. and d.c. sides are important factors in the generation of overvoltages.

Overvoltages in an HVDC substation may originate from either the a.c. system or from the d.c. line or cable, or from in-station faults. The nature of the a.c. and d.c. systems shall be taken into account as well as the transient and dynamic performance of the valves and the controls and worst case combinations shall be evaluated when studying overvoltages.

### 11.2 *Protection schemes using surge arresters*

Only gapless metal-oxide surge arresters are considered in this report for overvoltage protection of HVDC substations. Figure 18, page 67, shows an arrester protection scheme for an HVDC substation connected to an overhead d.c. line. Figure 19, page 68., shows a similar scheme for protection of a back-to-back substation. Figure 20, page 69, illustrates arrester protection on the a.c. side including a.c. filter arresters. Figure 21, page 70, shows an arrester protection scheme for an HVDC substation with series-connected convertors.

The arresters connected across the valves and on the d.c. side are subjected to different combinations of direct and alternating voltages, to harmonic voltages and to commutation overshoots. They should be designed to withstand the resulting stresses.

Arrester requirements shall often be determined through an iterative procedure. Energy absorption requirements imposed on the arrester determine its size and characteristics. These in turn affect the overvoltage level and arrester discharge currents. Arrester stresses are discussed further in 11.7.

### 11.3 *Switching overvoltages and temporary overvoltages on the a.c. side*

Switching overvoltages and temporary overvoltages (see definition in IEC 71-1) occurring on the a.c. side are important to the study of arrester applications. They determine the overvoltage protection and insulation levels of the a.c. side of the HVDC substation. They also influence valve insulation co-ordination.

For the special case of disconnectors located between the convertor transformers and the convertor bridge, protection of the convertor transformer valve windings shall be provided when these disconnectors are in an open position.

Overvoltages discussed in this subclause are generated by the a.c. side switching operations and fault events described in clauses 3 and 4 of this report.

### 11.4 *Switching overvoltages and temporary overvoltages on the d.c. side*

Except for the a.c. side overvoltages transmitted through the convertor transformers, the d.c. side insulation co-ordination for switching overvoltages and temporary overvoltages is mainly determined by fault and switching generated overvoltages on the d.c. side.

Events that shall be considered are d.c. line-to-earth faults, d.c. side switching operations, events resulting in an open earth electrode line, generation of superimposed a.c. voltages due to faults in the convertor control, misfiring, commutation failures, and earth faults and short-circuits within the convertor unit.

In systems involving a combination of d.c. cables and overhead lines, arresters may be needed at the cable terminations to protect them from overvoltages.

### 11.5 *Lightning and steep fronted surges*

The different sections of HVDC substations shall be examined in different ways for lightning surges. The sections are:

- a.c. switchyard section from the a.c. line entrance up to the line side terminals of the convertor transformers;
- d.c. switchyard section from the line entrance up to the line side terminal of the smoothing reactor;
- convertor bridge section between the valve side terminals of the convertor transformers and the valve side terminal of the smoothing reactor.

The convertor bridge section is separated from the other two sections by series reactances, i.e., at the one end inductance of the smoothing reactor and at the other end, the leakage reactance of the convertor transformers. Travelling waves such as those caused by lightning strokes on the a.c. side of the transformer or on the d.c. line outside of the smoothing reactor are attenuated by the combination of series reactance and earth capacitance to a shape similar to switching surges. Consequently they should be considered as part of the switching surge co-ordination.

The a.c. and d.c. switchyard sections have low impedance compared with overhead lines. The differences from most conventional a.c. switchyards are from the presence of a.c. filters, d.c. filters and possibly large shunt capacitor banks, all of which may have attenuating effect.

Steep-fronted surges, other than those caused by lightning, shall also be considered in the equipment design and testing as well as for insulation co-ordination. Such surges, caused by earth faults in the HVDC substation, are important for insulation co-ordination of the valves. These surges typically have a front time of the order 0,5 μs to 1,0 μs and durations up to 10 microseconds. The values and waveshapes to be specified should be determined by digital simulation studies.

In the a.c. switchyard section, steep fronted surges with front times of 5 ns to 150 ns may also be initiated by operation of disconnectors in gas-insulated switchgear. Also in the operation of $SF_6$ power circuit breakers, steep front overvoltages with front times of some tens of nanoseconds can appear.

### 11.6 *Protective margins*

Conventional procedures for insulation co-ordination are generally applied for insulation in HVDC substations. Alternatively, a statistical procedure can be used for self-restoring "insulation.

In the conventional procedure, the maximum overvoltage to be expected at a specific location is established, based on the characteristics of the overvoltages and the protective devices (the surge arresters).

The maximum current through a surge arrester should be established through a digital computer or an HVDC simulator study. The maximum current or a higher value is defined as the co-ordinating current. The voltage across the arrester that corresponds to this current is the protection level. In the case of switching overvoltage it is referred to as the Switching Impulse Protective Level (SIPL). The corresponding quantity for lightning overvoltages is called the Lightning Impulse Protective Level (LIPL).

The maximum overvoltage on the equipment is given by the protective level of the arrester or the arrester combination across the equipment, including the influence of the connections between the equipment, the arresters, and the earth.

When the maximum overvoltages have been determined, the corresponding insulation levels, i.e., the Switching Impulse Withstand Voltage (SIWV) and the Lightning Impulse Withstand Voltage (LIWV) as defined in IEC 71-1 can be established for the equipment to be protected by the surge arresters, taking into account protective margins.

The protective margin can be expressed as:

$$\text{Margin} = (\text{Safety factor} - 1) \times 100\ \%$$

where the Safety Factor is defined in IEC 71-1 as:

$$\text{Safety factor} = \frac{\text{Switching or lightning impulse withstand voltage}}{\text{Maximum overvoltage}}$$

Practice on a.c. systems provides one basis for selecting margins, and the extensive successful experience on existing HVDC systems provides additional data for establishment of criteria for selecting margins. Also the use of metal oxide surge arresters results in more consistent protective levels than was possible with prior arrester technology.

For switching impulse surges, a 15 % margin for the valves has been widely used. However for certain specific applications a 10 % margin has been used.

For lightning impulse surges a 15 % to 20 % margin has been widely used for the valves. Protection of other equipment should apply a 15 % to 20 % margin for switching impulse surges and a 20 % to 25 % margin for lightning impulse surges. Use of these margins in past practice has resulted in successful experience.

For steep front surges with front time less than or equal to 0.5 µs a 20 % to 25 % margin over the maximum overvoltage level is appropriate for valves as well as other equipment. Penetration into the valves of extremely steep front surges should be avoided.

The major reasons for selection of a lower margin or safety factor for the valves than for other equipment are that the valves are usually protected by surge arresters directly connected across them and the ageing process for thyristor valves is different from that of conventional power equipment such as power transformers, because failed thyristors are replaced at the times of regular service inspections. The valves shall be designed such that other insulation than thyristors has higher withstand strength and therefore automatically provides higher margins.

Required levels of protective margins described above should be specified.

### 11.7 *Arrester duties*

Please refer to figures 18 to 19, pages 67 to 68, for all arrester designations in this discussion.

#### 11.7.1 *A.C. bus arresters ($A_1$ and $A_2$)*

The a.c. side of an HVDC substation will usually be protected by arresters at the convertor transformers ($A_1$) and depending on the station configuration at other locations ($A_2$). These arresters are designed according to the criteria for conventional a.c. applications considering network earthing and lightning, switching, and temporary overvoltages. Because of possible saturation of the convertor transformers and low frequency resonances between the filters and the a.c. system, in particular at clearing of faults, high overvoltages of long duration may appear. The arresters may then need to be designed for high current and high energy dissipation.

### 11.7.2 *Arrester across filter reactors (FA)*

The events to be considered with respect to filter arrester duties are switching and temporary overvoltages on the a.c. bus and discharge of the filter capacitor through the arrester during earth faults on the filter bus. The former determines the required SIPL and the latter the LIPL and the energy discharge requirement. In certain cases, high energy discharge duties may also result from conditions of low order harmonic resonance, or due to low order non-characteristic harmonics generated by unbalanced operation during a.c. system faults (see 4.3.7).

### 11.7.3 *Valve arresters (V)*

The events to be considered with respect to valve arrester duties are:

- limitation of switching surge voltages and temporary overvoltages transmitted from the a.c. side;
- discharge of the d.c. line, d.c. filter, and valve hall capacitances during an earth fault between the convertor bridge and the high potential convertor transformer;
- current extinction in only one commutating group;
- discharge of lightning surges resulting from shielding failures.

The first three types of events determine the arrester stresses of switching surge type. These often lead to high energy absorption capability requirements for the arresters.

The level of forward protective firing of the valves shall be co-ordinated with the protective characteristics of the arresters. When the level of the forward protective firing of the valves shall be greater than the protective characteristics of the arresters, this should be specified.

In the case of parallel connected convertor units in rectifier operation, an earth fault between the convertor bridge and the high potential convertor transformer will impose additional energy absorption requirements on the affected arresters because of the fault currents fed from the parallel connected convertor unit.

Valves should be designed to withstand the expected maximum current commutated from the directly parallel connected arresters when the valves turn on during the arrester discharging.

### 11.7.4 *Mid-point d.c. bus arrester (M)*

Application of a mid-point d.c. bus arrester is sometimes used to reduce the insulation level requirements on the valve side of the convertor transformers.

Its duties are determined by current extinction in the lower six-pulse bridge and by lightning surges resulting from shielding failures. Data for this arrester are of the same order of magnitude as those for the valve arresters.

### 11.7.5 *Convertor unit d.c. bus arresters (CB) and convertor unit arresters*

The high voltage convertor unit bus can be directly protected by a convertor unit d.c. bus arrester connected between the bus and earth, figure 18, page 67, Arrester "CB". For series connected convertor units as shown in figure 21, page 70, usually a combination of a convertor unit arrester, Arrester "C", connected between the d.c. terminals of the high voltage convertor unit and a convertor unit d.c. bus arrester "CB2" for the low voltage convertor unit is used.

Since the protection levels of both the convertor unit d.c. bus arrester and the convertor unit arrester are of the order of twice the nominal d.c. voltage, these arresters will normally not be exposed to high discharge currents from switching surges. Their characteristics are determined from the steady-state d.c. voltage levels. In the case of series connected convertor units an additional requirement on arresters "$E_1$" and "$E_2$" is the discharge of the d.c. line when one convertor unit is short-circuited.

### 11.7.6 *D.C. bus and d.c. line arresters (DB and DL)*

The characteristics of the d.c. bus and d.c. line arresters are determined from consideration of the maximum operating voltage as well as lightning and switching surges. The d.c. bus arrester "DB" determines the insulation level of the d.c. pole equipment. On HVDC systems incorporating cables, the protective levels of the d.c. line arrester "DL" may have to be selected based on consideration of the cable withstand characteristics.

When the HVDC line comprises overhead line sections as well as cable sections, consideration should be given to the application of surge arresters at the cable-overhead line junctions to prevent excessive overvoltages on the cable due to reflection of travelling waves.

### 11.7.7 *Neutral bus arresters ($E_1$ and $E_2$)*

The operating voltage for the neutral bus arresters is normally low. At balanced bipolar operation it will be practically zero. During monopolar operation it will consist mainly of a small d.c. voltage corresponding to the voltage drop in the electrode line or the metallic return conductor.

These arresters are provided to protect equipment from lightning surges entering the neutral bus and to discharge large energies during the following events:

- earth fault on the d.c. pole;
- earth fault between the valves and convertor transformer;
- loss of return path during monopolar operation.

Their energy requirements will depend largely on the sequences to clear these faults.

### 11.7.8 *D.C. reactor arrester*

An arrester can be connected in parallel with the d.c. reactor to protect it from subtractive lightning impulses that could otherwise impose excessive overvoltages across the reactor. Its use permits a reduction in the insulation requirements across the reactor winding.

### 11.7.9 *D.C. filter arresters (FD)*

The normal operating voltage of the d.c. filter reactor arrester is low and usually consists of one or more harmonic voltages. Arrester duties are determined mainly by transients resulting from earth faults on the d.c. pole.

### 11.8 *Prevention of protective relay action due to arrester currents*

Arrester currents may need to be taken into account when designing the relay protection for HVDC substations. In some cases arresters which carry large discharge currents, as for example the high energy neutral bus arresters, can be located within a differential protection zone. If so, such arrester currents may need to be measured and fed to the protection to avoid unwanted relay operations during events outside the protective relay zone which initiate arrester discharge currents.

### 11.9 *Insulation clearances*

Air clearances for outdoor insulation are in general based on the SIWV specified using normal correction factors due to electrode shapes.

Inside the valve buildings great care should be taken to achieve electrode shapes that minimize required clearance distances. Distances used are normally based on tests with the appropriate electrode shape. Inside the valve halls, distances are normally determined so as to achieve a 0,1 % flashover probability.

### 11.10 *Creepage distances for the insulation*

### 11.10.1 *Outdoor insulation*

The external insulation of outdoor insulators and bushings is determined mainly by its performance under polluted conditions at normal operating voltage. Insulators subjected to d.c. voltage perform differently than those subjected to a.c. voltage. D.C. insulators tend to become more polluted than a.c. insulators located in the same substation because the d.c. insulators attract charged particles.

Depending on the pollution level, insulator d.c. withstand voltage under polluted conditions is generally lower than the r.m.s. a.c. withstand voltage. The d.c. withstand voltage also seems to be more dependent on insulator shape.

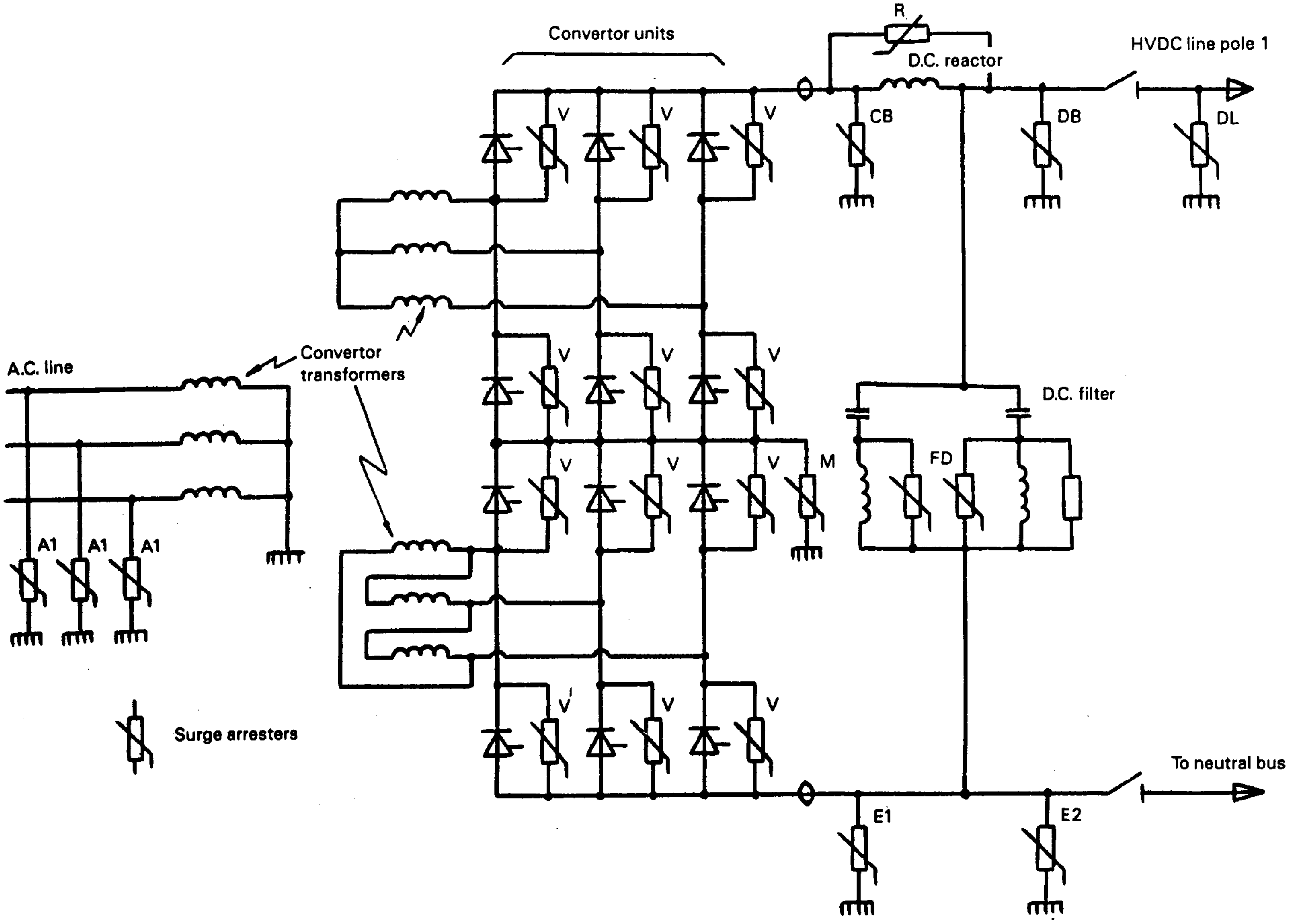
Specific creepage distances in the range of 2,5 to 4,6 cm/kV have been used for areas with light to medium pollution. For regions of heavy pollution, creepage values of 4,8 cm/kV and higher have been specified.

Operators of many HVDC installations have found it necessary to use insulator washing, greasing, or application of other coatings to the insulators to improve flashover performance.

Knowledge of station insulator performance under d.c. voltage stress and polluted conditions is limited. Further investigations are needed to establish reliable guidelines for determination of creepage distances.

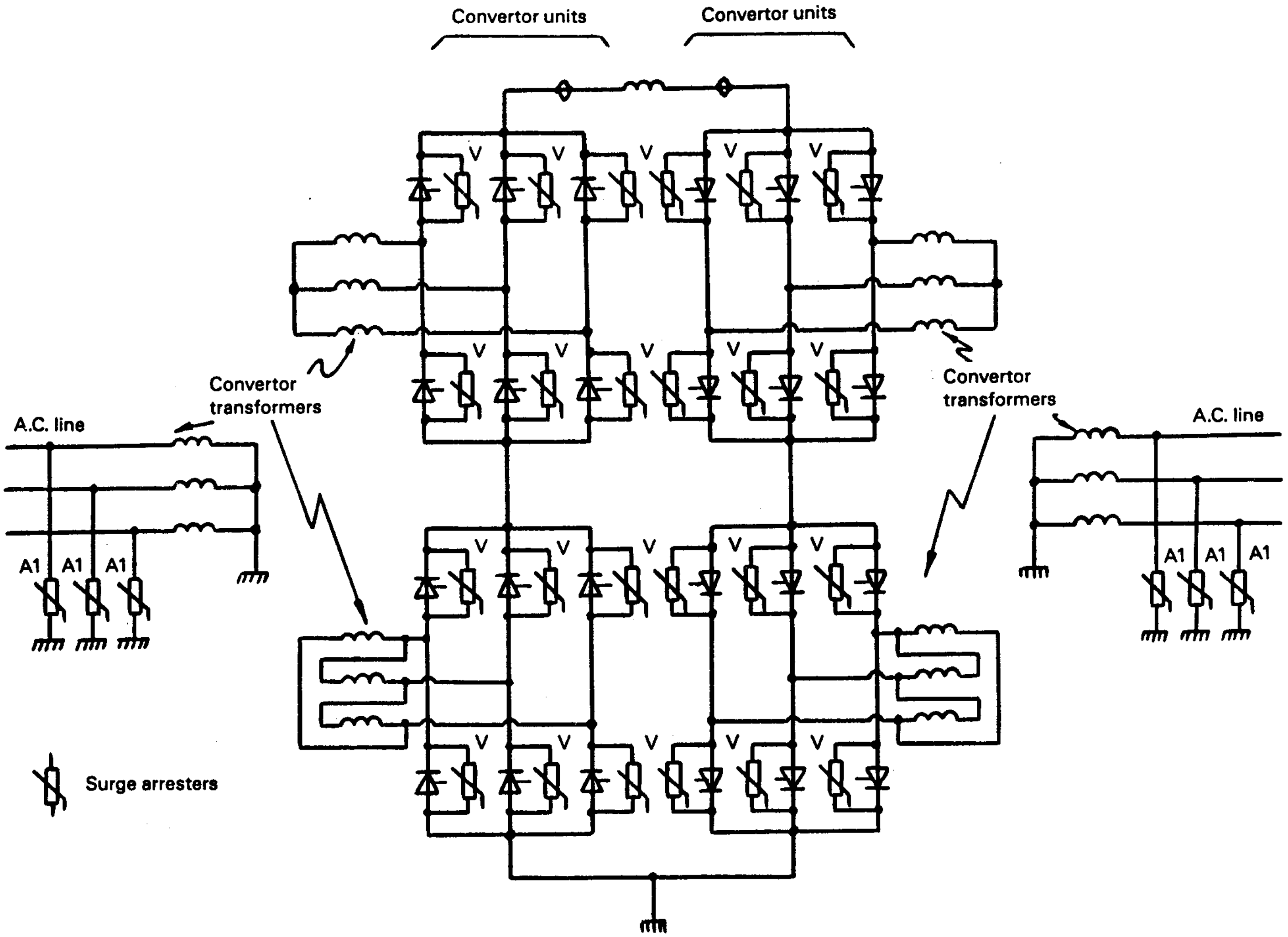
### 11.10.2 *Outdoor insulation*

Inside the valve halls a minimum specific creepage distance of 1,4 to 1,6 cm/kV of nominal d.c. voltage has been widely used. The environment is clean and the humidity is controlled. Creepage distance is therefore not a major consideration.



NOTE – For additional detail of an a.c. arrester example arrangement, see figure 20, page 139.

Figure 18 – Example of an arrester protection scheme for an HVDC substation



NOTE – For a.c. arrester arrangement, see figure 20, page 139.

Figure 19 – Example of a d.c. arrester protection scheme for a back-to back HVDC substation

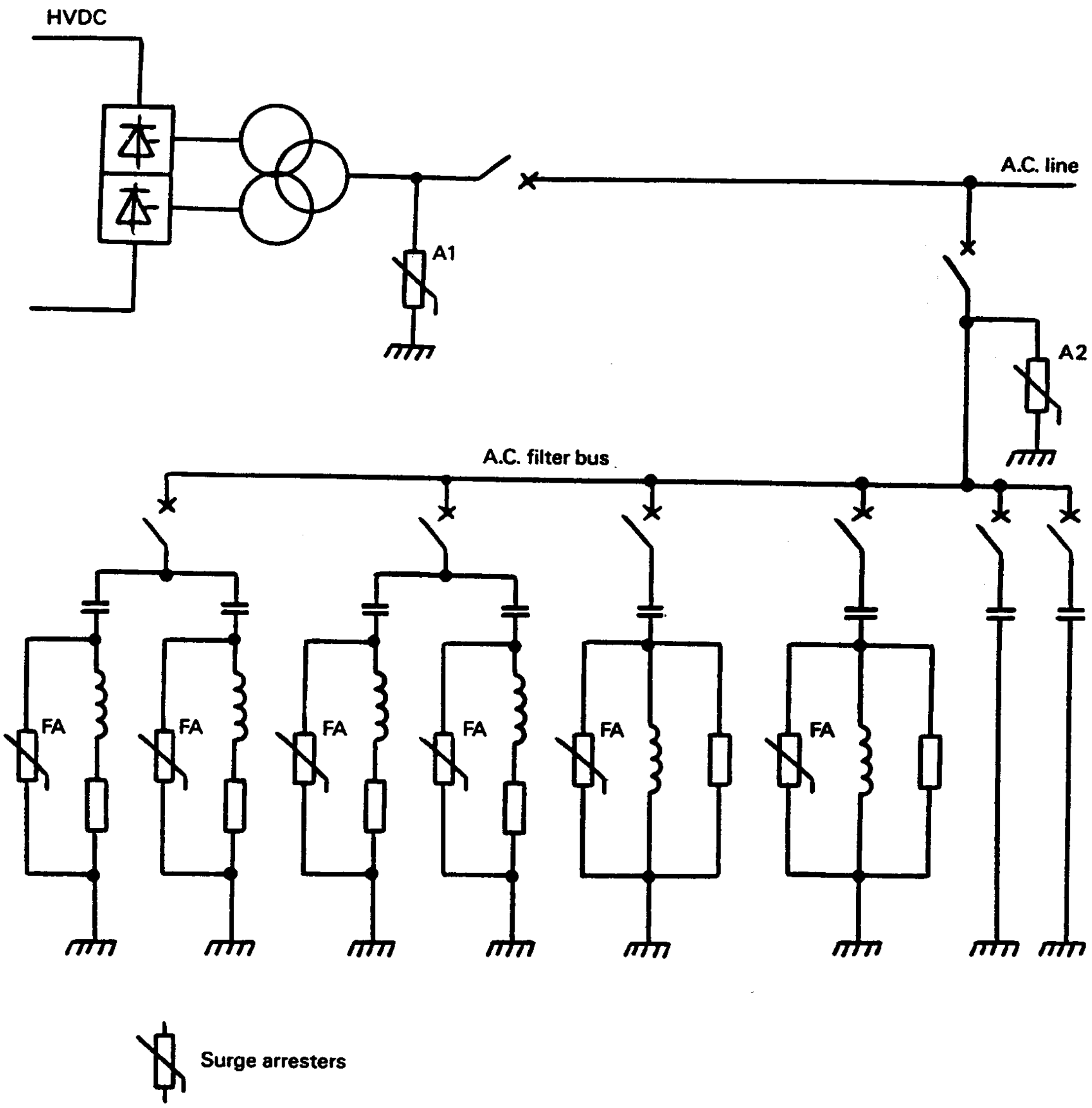


Figure 20 – Example of an a.c. arrester protection arrangement for an HVDC substation

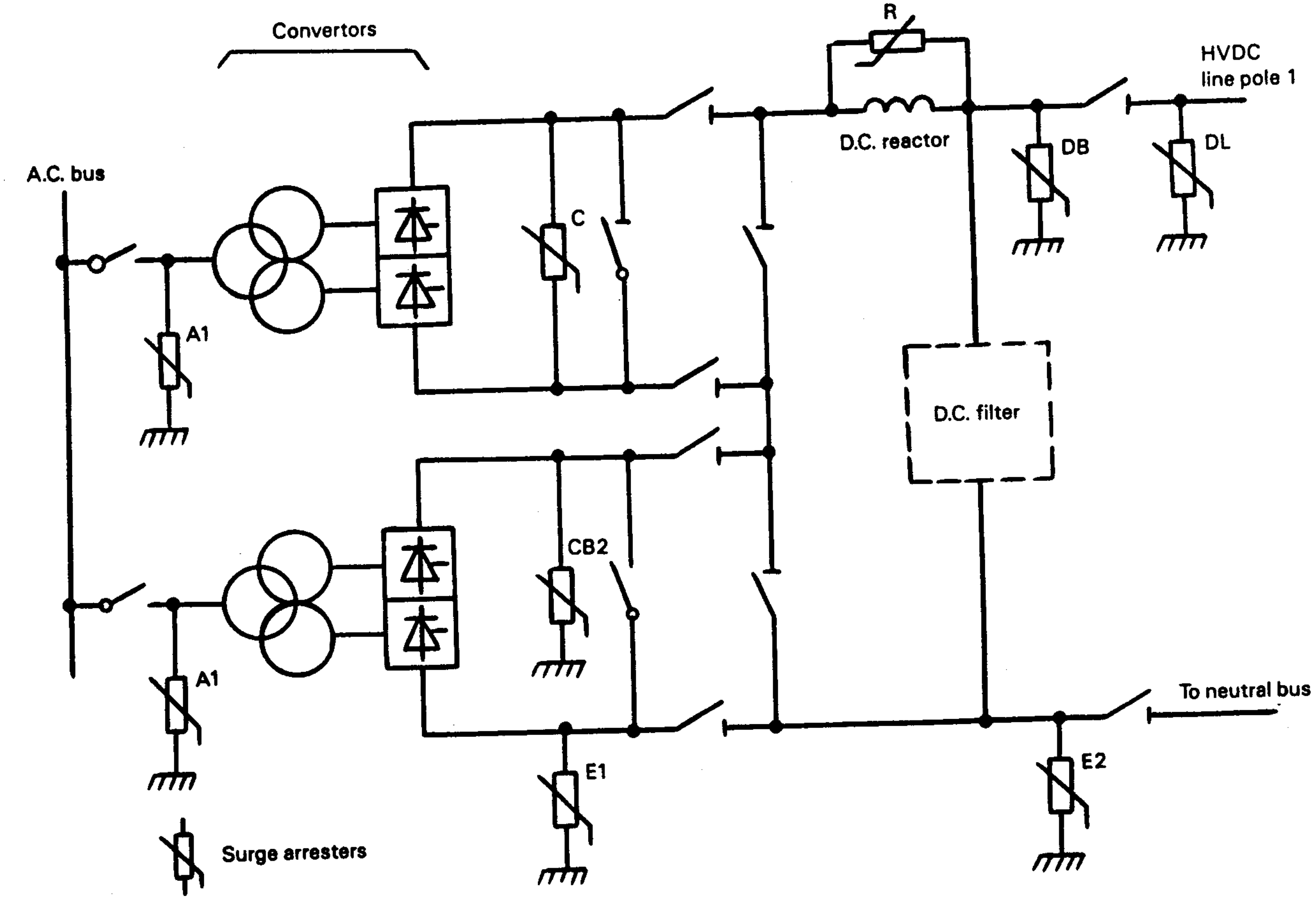


Figure 21 – Example of an arrester protection scheme in an HVDC substation with series-connected convertors

## 12 Telecommunication requirements

### 12.1 *General*

As indicated in IEC 919-1, different types of telecommunication can be used for the operation of an HVDC transmission link.

A main function of telecommunication in the operation of an HVDC link is to transmit control messages such as current or power orders, load and frequency control, etc. In addition it may also be used for supervision, operation and protection. Separate channels could be used for each function; however, often one channel can serve more than one function. In the allocation of channels protection requirements should be given priority.

Fault protection of station equipment and ability to restart after faults within the specified system recovery time should not be dependent on the telecommunication system. However the sending and receiving a.c. systems can be benefited by availability of telecommunication by for example, using it to diminish the impact of sudden changes in active and reactive power at the HVDC substation bus.

Protection of the HVDC substation equipments can be achieved reasonably without telecommunication and without impairing safe operation of the HVDC system. However compliance with requirements for minimum fault durations and short recovery times after faults may not be possible without telecommunication. Time settings that would be required for the protection for selectivity and safe switching sequences probably would not be compatible with the above objectives.

The telecommunication system should use a transmission path which should be secure from the effects of power system faults.

### 12.2 *Specific requirements - Telecommunication systems*

As discussed in clause 8, the basic d.c. line protection criteria, $dv/dt$, d.c. voltage and d.c current, need interterminal communication to cope with certain specific fault conditions:

- high resistance line faults;
- to give discrimination between d.c. line faults and inverter side faults including inverter commutation failures;
- for protection without use of d.c. circuit-breakers of d.c. lines operating in parallel to permit automatic switching sequences;
- for automatic paralleling and deparalleling of poles as needed for clearing of permanent pole faults line without using d.c. circuit-breakers.

Protection against inverter commutation failures is usually achieved by increasing the inverter extinction angle. However, some protection strategies order the rectifier to decrease the line current via a telecommunication channel as an alternative to voltage dependent control (clause 4).

A telecommunication channel in both directions can benefit operation of HVDC systems which use more than one convertor unit per pole by maintaining an equal number of convertor units in operation at each HVDC substation, following an automatic or manually-initiated unit blocking at each substation.

When a d.c. transmission is tied directly to a power station, the performance of the transmission may require control signals from the rectifier or the inverter to the power station. For example the signals could activate control sequences in the excitation or governing systems of the generators or it could optimize the number and loading of generator units and filter banks.

A telecommunication signal for each pole may be required to limit the current to a preset value following certain types of faults.

Similarly, a control signal for power reversal or change of power level can be used to enhance a.c. system stability for critical a.c. line outages (see clause 4).

Telecommunication channels for control and protection should be redundant and on a pole basis.

Telecommunication may also be used for line fault location.

### 12.3 *Consequence of telecommunication system outages*

For many of the requirements in 12.2, a lack of telecommunication may not cause trouble other than to increase recovery time after a fault.

However a communication outage could seriously degrade the d.c. system performance, for example by failing to distinguish between an a.c. side inverter fault and an inverter end d.c. line fault. If all telecommunications are involved in the outage, the whole d.c. transmission could be shut down by the d.c. line protection for inverter faults. A partial solution for such an occurrence could come from introduction of a time delay in the d.c. line protection immediately after loss of the telecommunication.

Overall a.c. system voltage control on the rectifier and the inverter end can impose a requirement for telecommunication. Consequences of loss of these communications on a.c. system operation should be carefully considered.

### 12.4 *Special considerations for power line carrier (PCL) systems*

Power line carrier (PLC) performance may suffer from transient faults in the pole and shield wire conductors sufficiently to degrade performance of the control and protection systems, thus affecting the HVDC system performance. To minimize such effects the following requirements should be specified for the PLC system:

- for a carrier system using a pole conductor and a shield wire as a communication path, the insulation of the shield wire should be designed to avoid scintillation during normal operation and overvoltage conditions considered in the HVDC system design;

- for a fault on the d.c. line or during a flashover of a shield wire insulator, the degradation of the power line carrier signal should be minimized sufficiently to avoid impairment of the specified HVDC system transmission performance level;

- carrier frequencies chosen for the protection and control channels should be as high as possible to avoid carrier interference produced by the convertor stations. A power line carrier filter may be required if the frequency selections do not avoid such effects.

In addition the following sources of transient disturbances on PLC over HVDC transmission lines should be carefully examined:

- interference from noise coupled from the electrode line;
- interference from a.c. lines paralleling or crossing the d.c. transmission line;

- interference due to pole-to-pole coupling on the HVDC line.

## 13 Auxiliary systems

### 13.1 *General*

The auxiliary systems of an HVDC substation are the support sources required to enable the HVDC system to produce its full range of power outputs, to enable the station to be maintained in good running condition and to allow the system to be safely shutdown.

These auxiliary systems can be broadly classified in two major groups, the electrical and the mechanical auxiliary systems.

### 13.2 *Electrical auxiliary systems*

#### 13.2.1 *General requirements*

Steady-state considerations of electrical auxiliary systems were discussed in IEC 919-1. This Part 2 discussion includes those aspects of electrical auxiliary system performance and requirements related to or which support the performance of HVDC systems during fault and switching-initiated transients.

The electrical auxiliary systems of HVDC substations are nearly always supplied from the a.c. networks to which the rectifier and inverter stations are connected. Consequently, faults in the a.c. networks or on the a.c. feeders which supply auxiliary power to HVDC substations could influence the performance of the auxiliary equipment and as a result the performance of the HVDC transmission. General practice then requires at least two main independent sources.

Although the load on the auxiliary system is usually only 0,2 % to 1 % of the HVDC substation rating, the security of the HVDC system depends vitally upon the correct operation of the auxiliary system during faults and switching transients, and the specification of the electrical auxiliary system should therefore emphasize this greater importance. In consequence it is generally appropriate that the electrical auxiliary system of a large HVDC substation should be much more complex and extensive than for a small HVDC substation.

Station auxiliary power loads can be classified in three categories: essential, emergency and normal loads. Essential loads are those necessary to assure the nominal power transmission capability of the HVDC substation. Emergency loads are those which should be in operation or should be ready to operate with minimum delay in the event of a power failure on the main a.c. bus. The normal or other loads in the station are those which are not closely related to the station's power conversion capability.

In the essential category are those loads such as the control and protection systems which cannot be interrupted or be exposed to transients. They are often described as the first grade auxiliary power loads. They are most often supplied from low voltage a.c. auxiliary power busbars through convertors from batteries or uninterruptable power supplies with redundant battery chargers.

To achieve 100 % redundancy and the necessary high degree of reliability, the essential load buses are nearly always supplied from two main independent power sources. They are arranged with automatic changeover to allow one of the primary sources to feed all loads in this category in the event of failure in the other source. Consideration should be given to the simultaneous interruption of both main power sources with respect to the design of the HVDC substation equipment and the auxiliary system.

Design of the automatic transfer might be arranged for normal parallel operation, minimum time delay transfer, or intentional time delay transfer depending on the HVDC substation's requirements as to the allowable interruption time in such power supplies or load synchronization constraints, etc.

Loads which do not require 100 % redundancy are often fed from one of two feeders which can be selected by changeover switches located near the equipment being served.

A special problem for regions subject to freezing temperatures is provision of an alternative power source to avoid freezing of some systems such as, oil lines, diesel fuel supplies, primary water systems, etc., in the event of complete power blackouts.

The auxiliary electrical systems should be designed to operate satisfactorily under full and overload HVDC transmission capacity following disturbances on the a.c. systems. The undervoltage operating limits for the auxiliary systems after a.c. fault clearing should be consistent with the HVDC link low voltage operating criteria.

Design of the auxiliary systems should take into account expected long duration fluctuations in the a.c. supply sources and operate satisfactorily under anticipated operating conditions in the supplying a.c. system.

### 13.2.2 *Specific requirements*

Each pole should have its own independent and completely duplicated auxiliary supply for its essential loads. Consideration should also be given to switching and transfer arrangements, during loss of service to one pole, for supplying auxiliary service from the auxiliary service of the other pole.

The auxiliary electrical system should be designed to ensure that after a short temporary interruption, caused by a disturbance in the a.c. system interfacing the HVDC substations, it will not prevent re-establishment of HVDC power transmission within the recovery time specified, after supply to the auxiliary service is re-energized.

The auxiliary electrical system should operate without interruption or shut down of any auxiliary system over the specified range of over and under frequencies for the HVDC link.

Uninterruptible power supplies should maintain output frequency and voltages within the limits required by the auxiliary systems it feeds, so that the operation of valve groups will not be impaired, and to assure continuous protection co-ordination during short time interruptions of up to 2 s of the a.c. power supply to the auxiliary systems.

Control and protection design of auxiliary electrical systems should follow similar practices used for a.c. low voltage industrial or commercial applications, with special regard for the fault clearing speed and protective device selectivity. Particular attention is suggested to:

- avoid paralleling two or more main auxiliary supplies to limit the short-circuit duties of the auxiliary service components;
- provide means for assuring synchronism when two buses are to be paralleled during automatic changeover from one source to another;
- changeover being accomplished within the time requirements of the particular load being supplied with due allowance for the voltage conditions on the buses involved.

### 13.3 *Mechanical auxiliary systems*

The mechanical auxiliary systems for an HVDC substation include the following important systems: valve cooling; synchronous compensator cooling; compressed air; fire detection, protection and extinguishing; insulating oil; diesel oil; water supply; drainage and sewage; air conditioning; ventilation; and mechanical load handling facilities.

The above systems are required so that full electric power transmission can be maintained on the HVDC system. The valve cooling system is probably the most important and critical.

The design of the convertors will determine the type of valve cooling system. Generally, it will be either air or liquid cooled. Cooling for a valve group should be dimensioned to handle the power losses from each valve group. Moreover provision should be made for stand-by or spare components so that the failure or shut-down of a fan, cooling pump, heat exchanger, etc. will not cause a reduction of d.c. transmission capacity under any reasonably expected combination of load and ambient conditions.

A supervisory and alarm system may well be included to monitor the auxiliary power functions essential to thyristor valve operation and cooling. Such functions might include:

- air-cooled valves: maximum incoming and outgoing air temperature for the thyristor assemblies; maximum air temperature to and from the heat exchangers; differential pressure across the valves; maximum and minimum temperature in the valve hall; pressure and air flow at critical locations in the air handling facilities; etc.

- water-cooled valves: deionized water temperatures from and to the valves; water level in expansion vessels; water conductivity; pressure drop across the valve cooling pipes; low water flow through a valve; water oxygen content if necessary; if a cooling tower is used, water temperatures and heat exchanger temperatures; and temperature and humidity of the valve hall air and air handling system.

The supervisory system should be arranged to give alarm warnings for low and high limits of the items described above, as well as for loss of pumps or fans, for low reserves of water and the need for refilling of storage vessels, and for water leakage in the thyristor valve structures, etc.

It should also give an alarm signal for such excursions from normal as: high temperature of the deionized water or of the air to and from the valves; low water flow through a valve; or loss of too many pumps or fans, for which a trip signal might be initiated by the supervisory system.

Another mechanical system important for full power transmission is the cooling system for the HVDC transmission's reactive power supplies such as synchronous compensators and static compensators. An independent cooling system should be provided for each such reactive power supply system with sufficient redundancy of major or critical elements in its cooling system to minimize any reduction of transmitted HVDC power resulting from loss of one reactive power source.

Compressed air systems can be important for safe shutdown of the HVDC substation particularly if compressed air is required for operation of switching equipment.

Mechanical equipment in the HVDC substation shall be designed to operate satisfactorily during transients including those which result in over- or underspeed.

Other mechanical auxiliary systems are often provided for maintenance needs or for safety reasons. These are not directly related to the transient performance of an HVDC transmission system.

# ANNEX A
(informative)

## Bibliography

In addition to the standards referred to in IEC 919-1, the following publications are considered particularly useful reference materials, but the list may not be complete.

IEC standards

50 (371): 1984, *International Electrotechnical Vocabulary (IEV), Chapter 371: Telecontrol.*

50 (421): 1990, *Chapter 421: Power transformers and reactors.*

50 (436), *Chapter 436: Power capacitors (in preparation).*

50 (443), *Chapter 443: Switchgear, controlgear and fuses.*

50 (448): 1987, *Chapter 448: Power system protection.*

50 (471): 1984, *Chapter 471: Insulators.*

50 (521): 1984, *Chapter 521: Semiconductor devices and integrated circuits.*

50 (551): 1982, *Chapter 551: Power electronics.*

70: 1967, *Power capacitors.*

71: *Insulation co-ordination.*

76: *Power transformers.*

185: 1987, *Current transformers.*

186: 1987, *Voltage transformers.*

289: 1988, *Reactors.*

IEC Report

505: 1975, *Guide for the evaluation and identification of insulation systems of electrical equipment.*

---

(*Continued from second cover*)

| *IEC Pub No. with Year Referred to* | *Latest IEC Pub No. with Year* | *Title of the Latest IEC Publication* | *Corresponding Indian Standard* | *Title of Indian Standard* | *Degree of Equivalence* |
|---|---|---|---|---|---|
| 146 (1973) | 60146-1-1 (1991) and 60146-1-2 (1991) | Semiconductor convertors— General requirements and line commutated convertors — Part 1-1 : Specification of basic requirement and Part 1-2: Application guide | No ISS | — | — |
| 633 (1978) | 60633 (1998) | Terminology for high-voltage direct current (HVDC) transmission | 14801 : 2000 | Terminology for high-voltage current (HVDC) transmission | Identical to IEC 60633 (1998) |
| 700 (1981) | 60700-1 (1998) | Thyristor valves for high-voltage direct current (HVDC) power transmission— Part 1 : Electrical testing | Corresponding Indian Standard is under print | Thyristor valves for high-voltage direct current (HVDC) transmission: Part 1 Electrical testing | Identical to IEC 60700-1 (1998) |
| 60919-1 (1988) | 60919-1 (1988) | Performance of high-voltage d.c. (HVDC) system — Part 1: Steady-state conditions | Corresponding Indian Standard is under print | Performance of HVDC systems: Part 1 Steady-state conditions | Identical |
| 60919-3 (1999) | 60919-3 (1999) | Performance of high voltage d.c. (HVDC) system — Part 3: Dynamic conditions | Corresponding Indian Standard is under preparation | Performance of HVDC systems: Part 3 Dynamic conditions | — |

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test, shall be rounded off in accordance with IS 2:1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

## Bureau of Indian Standards

BIS is a statutory institution established under the *Bureau of Indian Standards Act*, 1986 to promote harmonious development of the activities of standardization, marking and quality certification of goods and attending to connected matters in the country.

## Copyright

BIS has the copyright of all its publications. No part of these publications may be reproduced in any form without the prior permission in writing of BIS. This does not preclude the free use, in the course of implementing the standard, of necessary details, such as symbols and sizes, type or grade designations. Enquiries relating to copyright be addressed to the Director (Publications), BIS.

## Review of Indian Standards

Amendments are issued to standards as the need arises on the basis of comments. Standards are also reviewed periodically; a standard along with amendments is reaffirmed when such review indicates that no changes are needed; if the review indicates that changes are needed, it is taken up for revision. Users of Indian Standards should ascertain that they are in possession of the latest amendments or edition by referring to the latest issue of 'BIS Catalogue' and 'Standards: Monthly Additions'.

This Indian Standard has been developed from Doc : ET 40 (3320).

### Amendments Issued Since Publication

| Amend No. | Date of Issue | Text Affected |
|---|---|---|
| | | |
| | | |
| | | |

BUREAU OF INDIAN STANDARDS

Headquarters:

Manak Bhavan, 9 Bahadur Shah Zafar Marg, NEW DELHI 110002
Telephones : 323 01 31, 323 33 75, 323 94 02
Telegrams : Manaksanstha
(Common to all offices)

| Regional Offices: | | Telephone |
|---|---|---|
| Central | : Manak Bhavan, 9 Bahadur Shah Zafar Marg<br>NEW DELHI 110002 | 323 76 17<br>323 38 41 |
| Eastern | : 1/14 C. I.T. Scheme VII M, V.I.P. Road, Kankurgachi<br>CALCUTTA 700 054 | 337 84 99, 337 85 61<br>337 86 26, 337 91 20 |
| Northern | : SCO 335-336, Sector 34-A, CHANDIGARH 160 022 | 60 38 43<br>60 20 25 |
| Southern | : C.I.T. Campus, IV Cross Road, CHENNAI 600 113 | 235 02 16, 235 04 42<br>235 15 19, 235 23 15 |
| Western | : Manakalaya, E9 MIDC, Marol, Andheri (East)<br>MUMBAI 400 093 | 832 92 95, 832 78 58<br>832 78 91, 832 78 92 |
| Branches | : AHMADABAD • BANGALORE • BHOPAL • BHUBANESHWAR • COIMBATORE • FARIDABAD • GHAZIABAD • GUWAHATI • HYDERABAD • JAIPUR • KANPUR • LUCKNOW • NAGPUR • PATNA • PUNE • RAJKOT • THIRUVANANTHAPURAM. | |

Printed at Printograph, New Delh, Ph.: 5726847